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SYNTHESIS AND ANALYSIS OF
ERTS PROGRAM
MIDTERM REPORT

WATER RESOURCES
SIGNIFICANCE, USER REQUIREMENTS, REMOTE SENSING APPLICATIONS

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15 November 1973

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SYNTHESIS AND ANALYSIS OF
ERTS PROGRAM
MIDTERM REPORT

WATER RESOURCES

SIGNIFICANCE, USER REQUIREMENTS, REMOTE SENSING APPLICATIONS

Contract NASW-2488
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TABLE OF CONTENTS

PREFACE

This report, prepared under Contract NASW-2488, presents and illustrates a methodology for deriving meaningful tasks for applying the technology of remote sensing to the management of earth's natural resources and environment.

Although this report deals with the specific field of Water Resources, the methodology developed is sufficiently general to allow its utilization in other areas of potential remote sensing application.

The report is compiled in a succint format for easy reading and assimilation of the information presented. The right-hand pages contain the significant information, generally in pictorial form, whereas the left-hand pages provide brief explanations and constitute the written text, which connects presented information in logical sequence.

I. METHODOLOGY AND STRUCTURE

The contemporary concept of water as a free or nearly free good will necessarily give way to more systematic and equitable delineations of costs and benefits. As costs escalate, ensuing economic pressures will generate increased competition and conflict, to be resolved only by truly comprehensive planning. In resolving optimum plans, there will be a struggle for supremacy between achievement of economic efficiency and attainment of social goals, including aesthetic considerations.

LOGIC FLOW OF INVESTIGATION

- Why are water resources important? How important?
- What are the major interests and concerns of users? How categorized?
- Who are the users? Represented by what agencies? How do the jurisdictions and roles of these agencies complement each other?
- What is the economic significance, the effort, the state of knowledge, and the structure of the management effort performed by water resources management agencies in each principal application?
- What branches of science and engineering do they use? What models? How do they collect and manipulate data?
- What kind of observable data do they need? How accurately, when, how often, where? How many of these can be acquired, directly or inferentially, from surface observations?
- What subset of these is obtained by ERTS? How well?
- To what degree do ERTS Program Significant Findings satisfy the above data requirements?
- How should ERTS research be focused to maximize the yield of the program?
- Can some observables, not visibly obtainable from ERTS, be obtained from indirect correlations? What specifications should a future ERTS system possess?
- What is the most significant role which NASA technology and capabilities can explicate in fostering national objectives in Water Resources?

STRUCTURE OF INVESTIGATION

- SOCIOECONOMIC SIGNIFICANCE OF WATER RESOURCES.
- PRINCIPAL REQUIREMENTS AND CONCERNS OF USERS.
- PRINCIPAL USERS; THEIR INTERESTS; FUNCTIONS; INTER-RELATIONSHIPS.
- PRINCIPAL CONCERNS AND APPLICATIONS OF WATER MANAGEMENT AGENCIES:
  - Flood Management
  - Erosion and Sedimentation
  - Snowmelt
  - . . . . .
- CURRENTLY AVAILABLE SCIENTIFIC AND ENGINEERING DISCIPLINES, MANAGEMENT AND DATA COLLECTIONS TOOLS.
- REQUIRED OBSERVABLES AND ROLE OF REMOTE SENSING IN ACQUIRING THE REQUIRED OBSERVABLES, BY ITSELF OR IN CONJUNCTION WITH A PRIOR KNOWLEDGE.
- PORTION OF REQUIRED OBSERVABLES WHICH ERTS CAN ACQUIRE.
- SIGNIFICANCE AND FIT OF INITIAL SIGNIFICANT FINDINGS BY ERTS.
- IMMEDIATE FOCUS OF ERTS INVESTIGATIONS IN WATER RESOURCES.
- DIRECTIONS OF FURTHER INVESTIGATIONS MOST PROMISING TO ENHANCE REMOTE SENSING CAPABILITIES.
- PLAN.

SOCIOECONOMIC SIGNIFICANCE OF WATER RESOURCES

WATER IS BECOMING SCARCE.

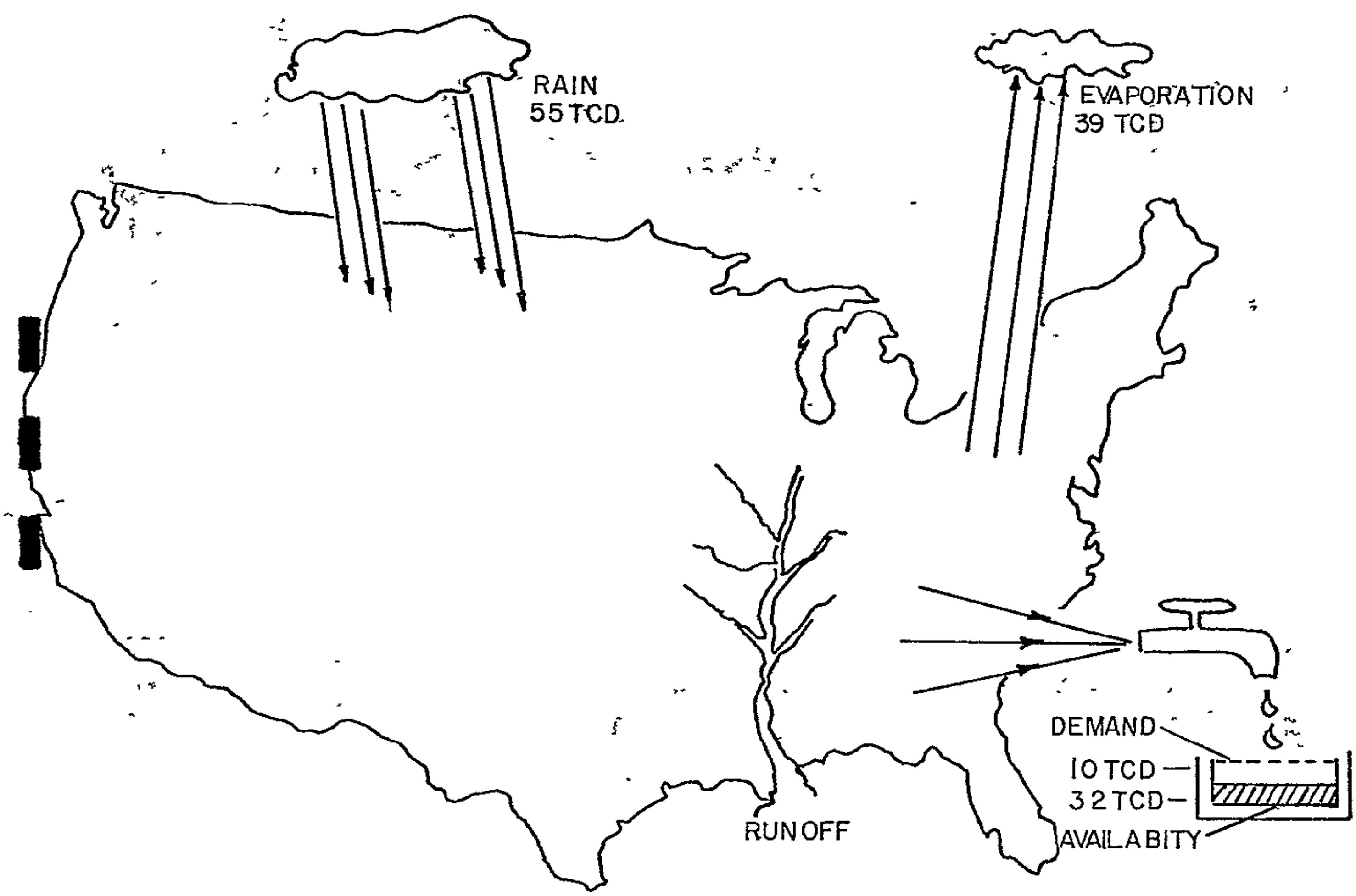
THERE ARE TWO SOURCES OF WATER:

CURRENTLY USED: PRECIPITATION
POTENTIAL: NEW TECHNOLOGY

NEW TECHNOLOGY, SUCH AS DESALINIZATION, IS AS YET ECONOMICALLY NON-COMPETITIVE.

PRESENT SOURCE IS ADEQUATE THROUGH 1990, PROVIDED UTILIZATION EFFICIENCY IS IMPROVED.

WATER RESOURCES PROJECTION-1990



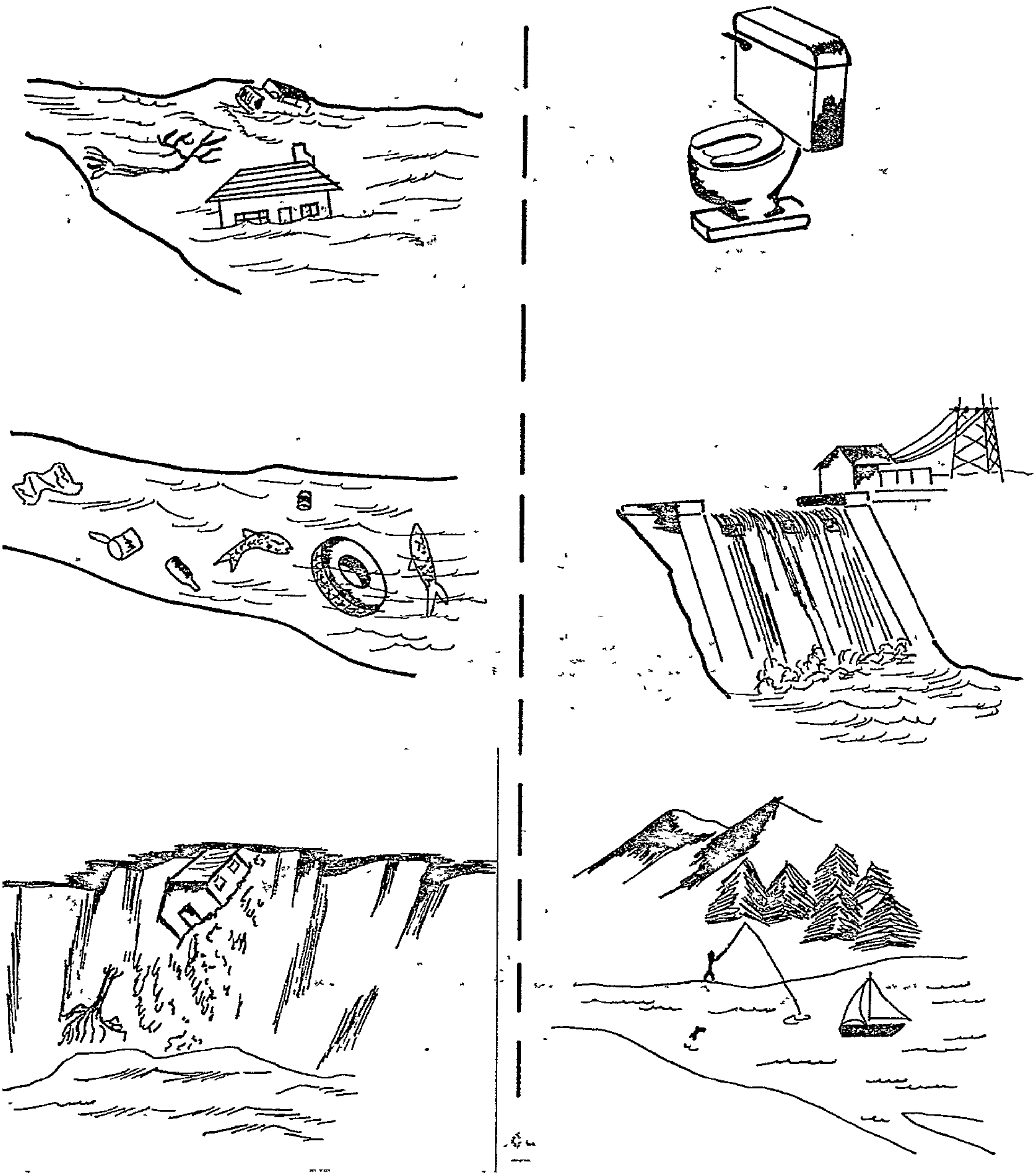
*TCD = TONS/CAPITA/DAY

MAJOR IMPACT OF WATER RESOURCES UPON THE PUBLIC

- EFFECTS OF WATER
  - Excess Water
  - Waterborne Substances
  - Hydrogeological Effects

- DEMANDS FOR WATER
  - Consumptive Uses
  - Flow Uses
  - On-Site Uses

CONCERNS | REQUIREMENTS



PRINCIPAL REQUIREMENTS AND CONCERNS OF WATER USERS

Water, like any natural phenomenon, can be beneficial or damaging, depending upon its impact on users, the degree of control, and the user's viewpoint.

For example, the excess water on a wetland can be viewed simultaneously as a nuisance by farmers or developers, and as a boon by sportsmen and conservationists. Floods can be damaging to homeowners, but beneficial to farmers by virtue of the fertilizing qualities of the deposited sediment.

In the U.S., however, the damage associated with the effects of water exceeds the benefits. The general user orientation is, therefore, directed at preventing the occurrence of these effects, or at alleviating their impact.

PRINCIPAL REQUIREMENTS AND CONCERNS OF WATER USERS

THE EFFECTS OF WATER

Excess Water

- Floods
  - Inundations
  - Flash
- Avalanches
  - Snowfalls
  - Glacier Collapse
- Wetlands
  - Reclamation
  - Management

Waterborne Substances

- Toxicants
- Disease Vectors
- Eutrophicants
- Inhibitors
- Aesthetics
- Thermal
- Sedimentary

Hydrogeological Effects

- Landslides
- Mudslides
- Soil Erosion & Sedimentation
- Subsidence
- Drought/ Desertification
- Salt Water Intrusions

DEMANDS FOR WATER

Consumptive Users

- Agricultural
  - Irrigation
  - Livestock
- Industrial
  - Process
  - Cooling
- Domestic
  - Sanitary
  - Consumptive
- Municipal
  - Sewage Processing
  - Aesthetic
  - Fire Fighting

Flow Users

- Hydropower
- Pollution Dilution/ Entrainment

On-Site Users

- Inland Navigation
- Recreation
- Commercial Fishing

Ultimate user of water: U.S. citizenry.

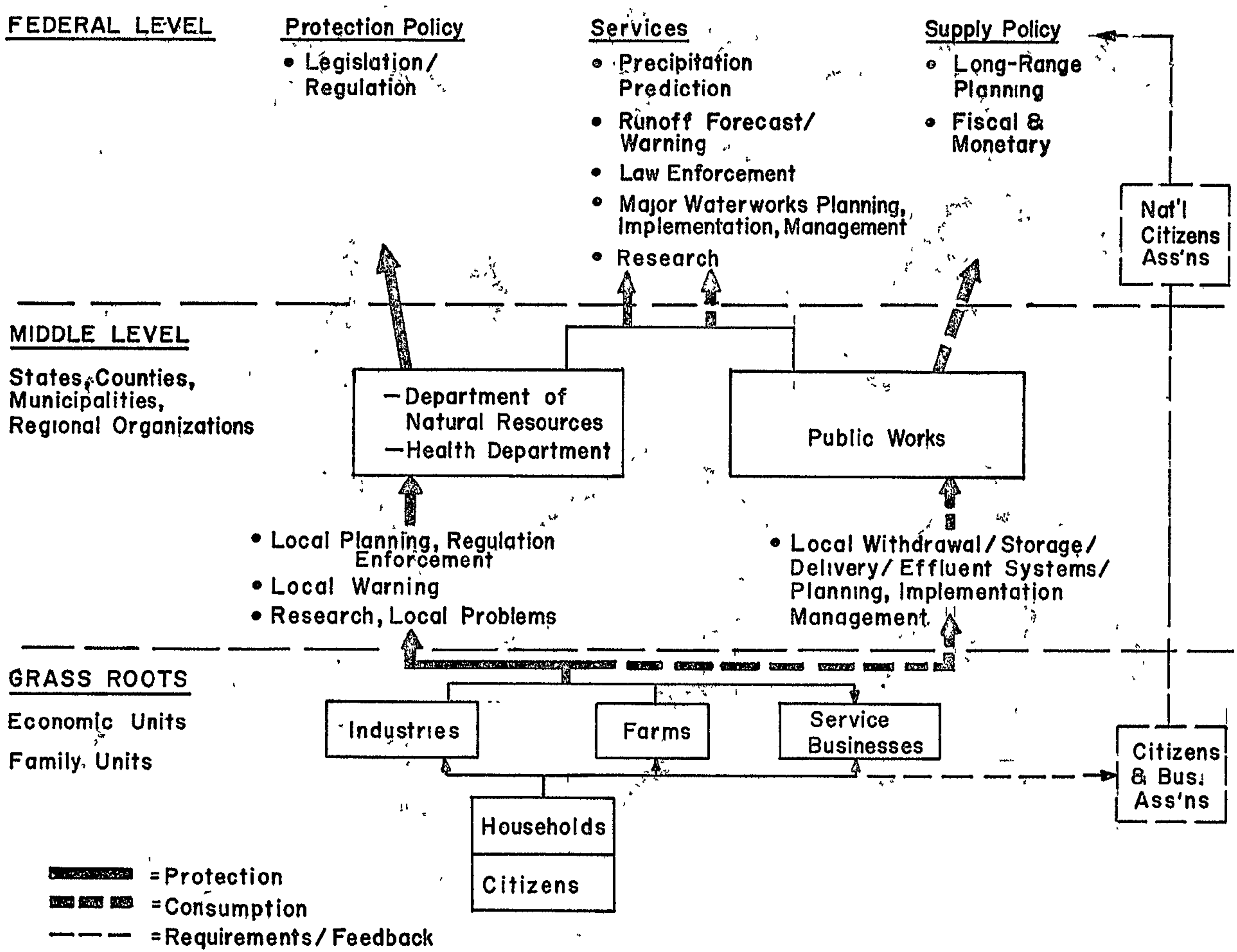
Citizens group into units to efficiently explicate the tasks of everyday life and economic production, and into politically-oriented associations for making their wishes known to authorities.

The first-level grouping is conveniently labeled as "Grass Roots" users. Its major interests are twofold: (1) protection against damages from water, and (2) provision of supply adequate to meet the needs of households, agriculture and industry.

At the middle-level lie those entities to whom the citizenry delegates the task of providing for, managing and regulating their local needs.

Agencies at the Federal level elaborate and provide policy guidance and services whose scope and data requirements transcend the local level's geographic domain and capabilities.

National citizens organizations provide their viewpoints and needs at this level primarily through the Legislative Branch.



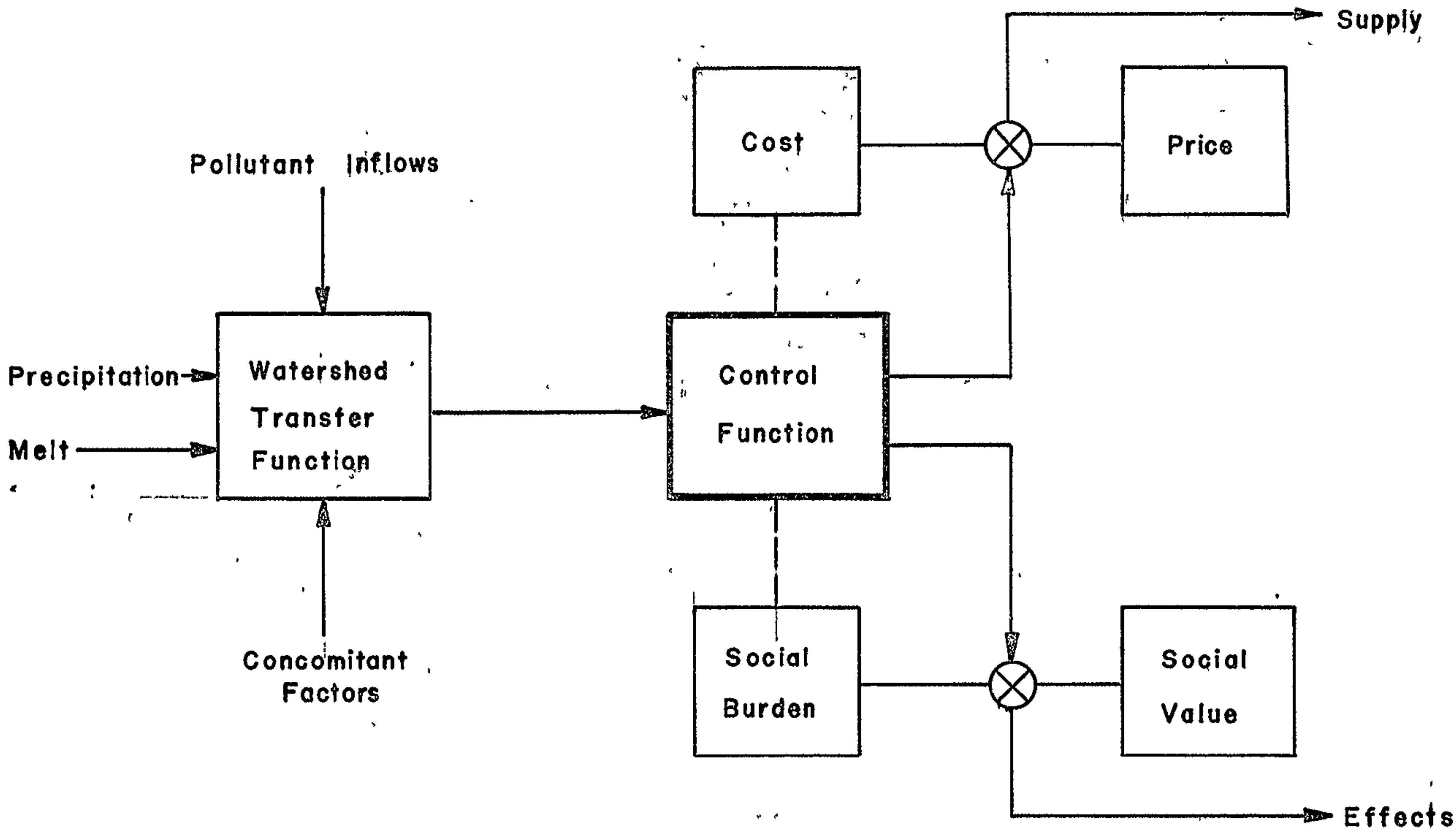
USER INTERESTS, FUNCTIONS, INTERRELATIONSHIPS

What is input to the user is output to the manager.

Water Management Agencies are tasked to service users by managing the effects and providing supply to match demand.

As demand increases, satisfying all needs of all users becomes increasingly expensive. The establishment of economic priorities becomes an ever more important element in the supply-demand system.

The manager's span of interest extends, therefore, from inputs to outputs, to economics, to social value judgements.

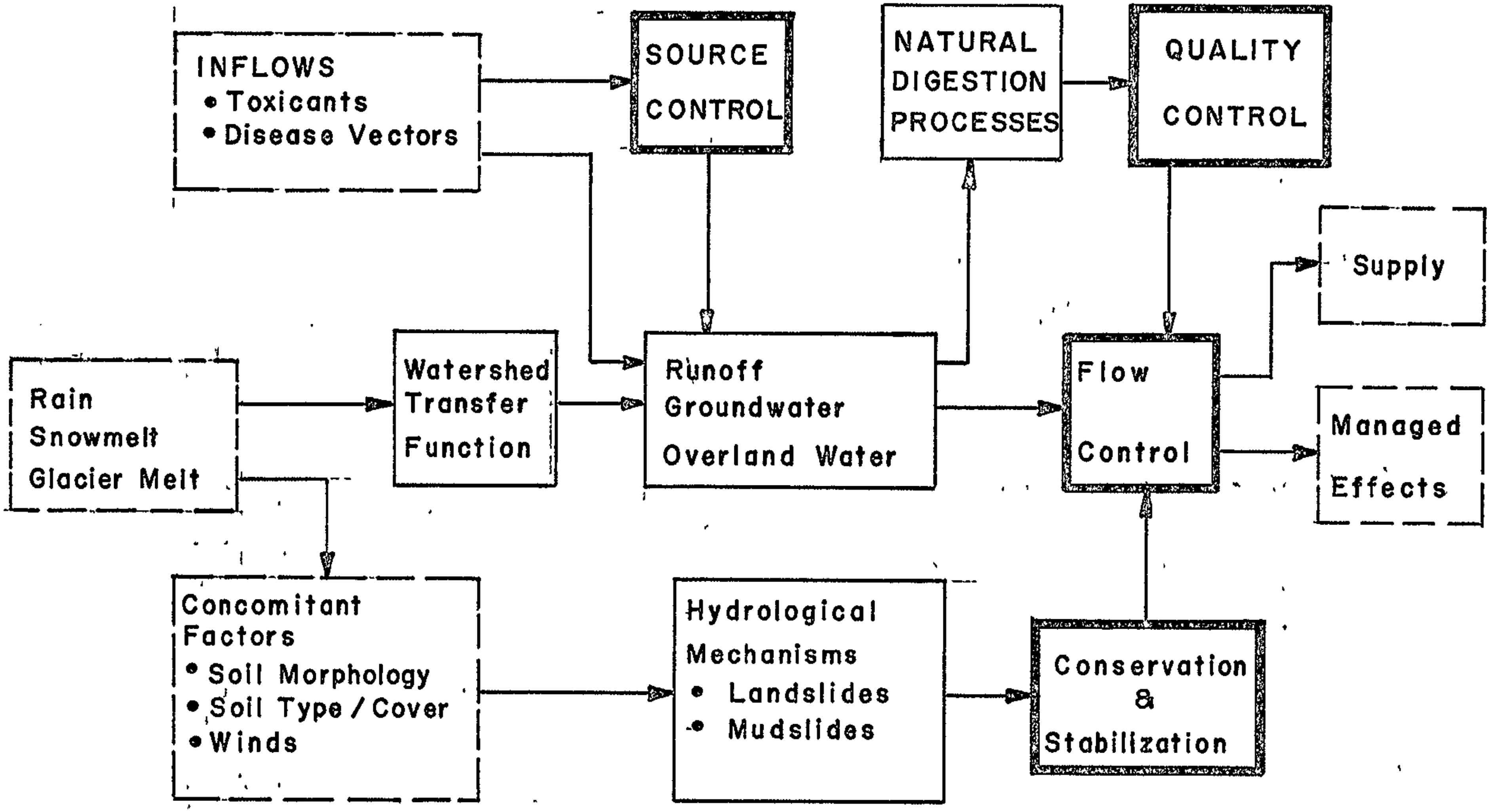


SPAN OF INTEREST OF WATER RESOURCES MANAGERS

Physical inputs, precipitation and snowmelt, acting through watershed transfer functions, generate "natural" water outputs. Flow control matches the statistical input quantities to the deterministic demand schedules.

Pollutant inputs undergo natural digestion processes in water. Quality control provides the water quality needed by users.

Water, acting with concomitant factors, gives rise to hydrogeological effects. Conservation and stabilization limit the damage from hydrogeological effects.



MAJOR PHYSICAL PROCESSES AND INTERACTIONS AFFECTING WATER RESOURCES MANAGERS

Inputs & Outputs	Physical Mechanisms	Control Functions

2. THE EFFECTS OF WATER

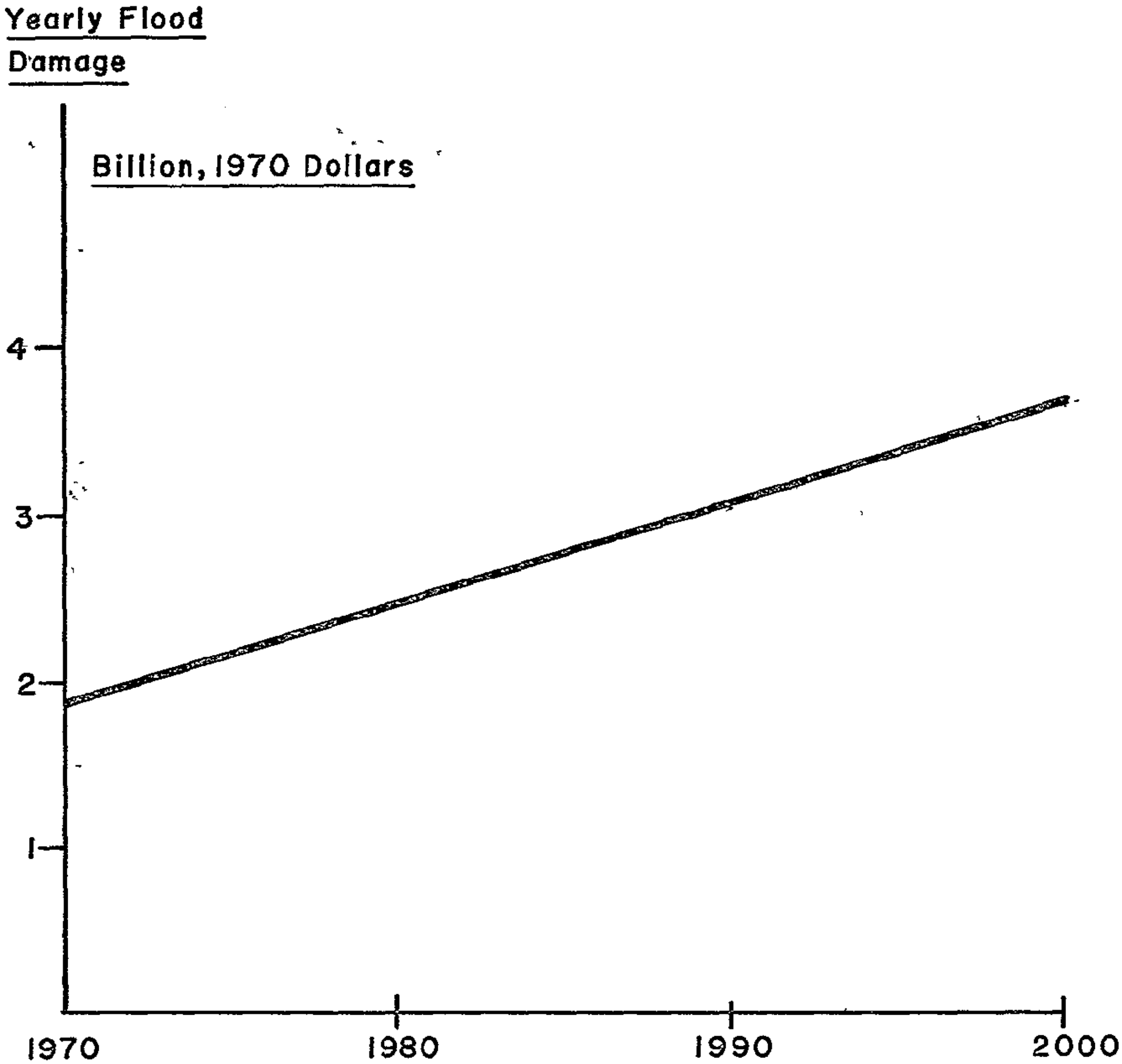
FLOODS

By far the most significant effect of water is represented by floods.

The economic significance of floods is measured by the damage they cause.

Current yearly damage is approximately $2 billion. From 1940 to 1970, the U.S. spent approximately $8 billion for flood damage mitigation.

If flood management and protection levels were fixed at their 1970 status, flood damage would increase as shown opposite, based upon forecasted economic growth in flood-prone areas.



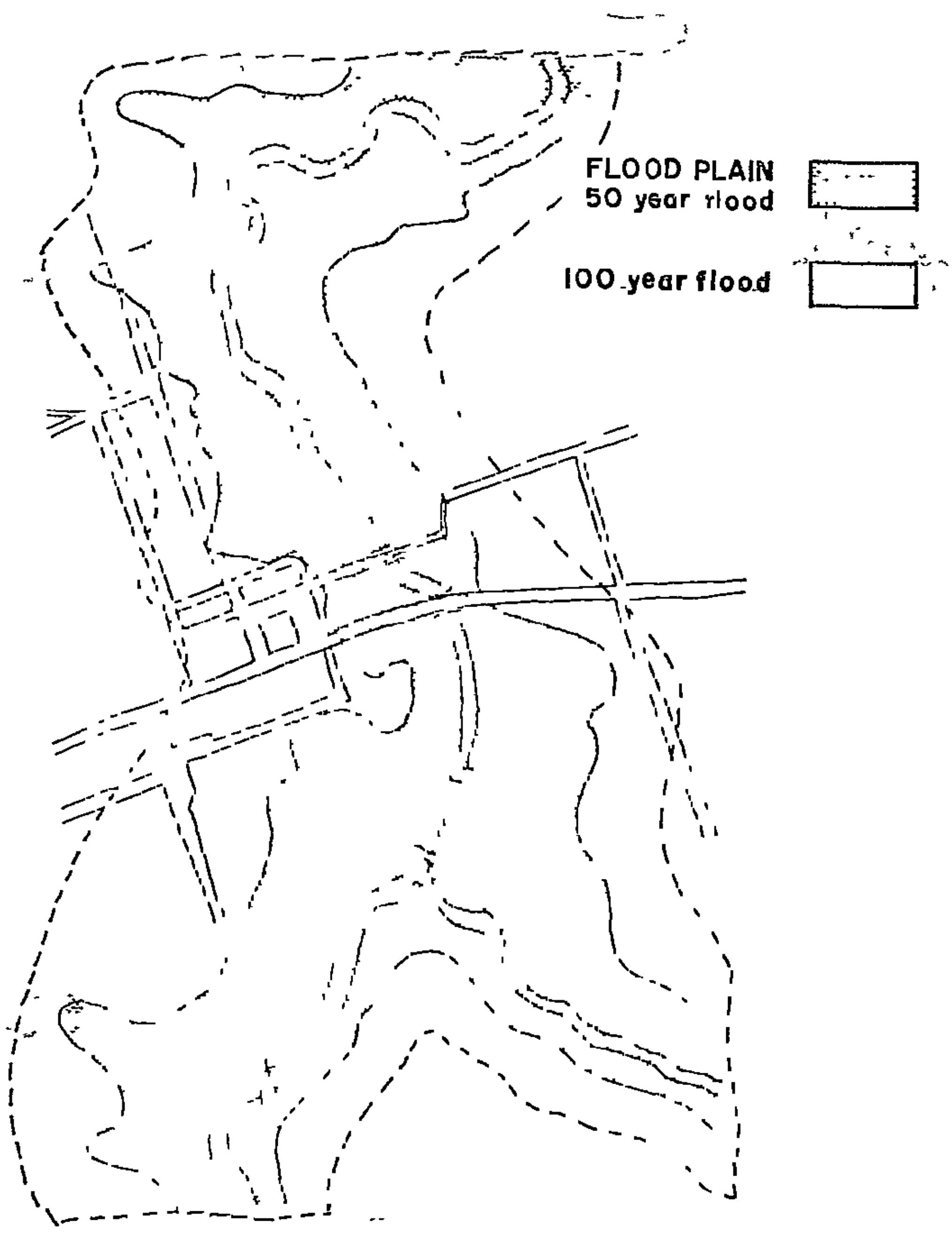
Yearly U.S. Flood Damage With Flood Management & Protection Fixed At 1970 Level.

The terrain surface which the flood can invade is called "flood plain".

Damage is related to the areal extent of the flood plain.

Flood plains account for approximately 90 million acres, or 5% of the U.S. land surface. Most of this land is endowed with desirable land use characteristics.

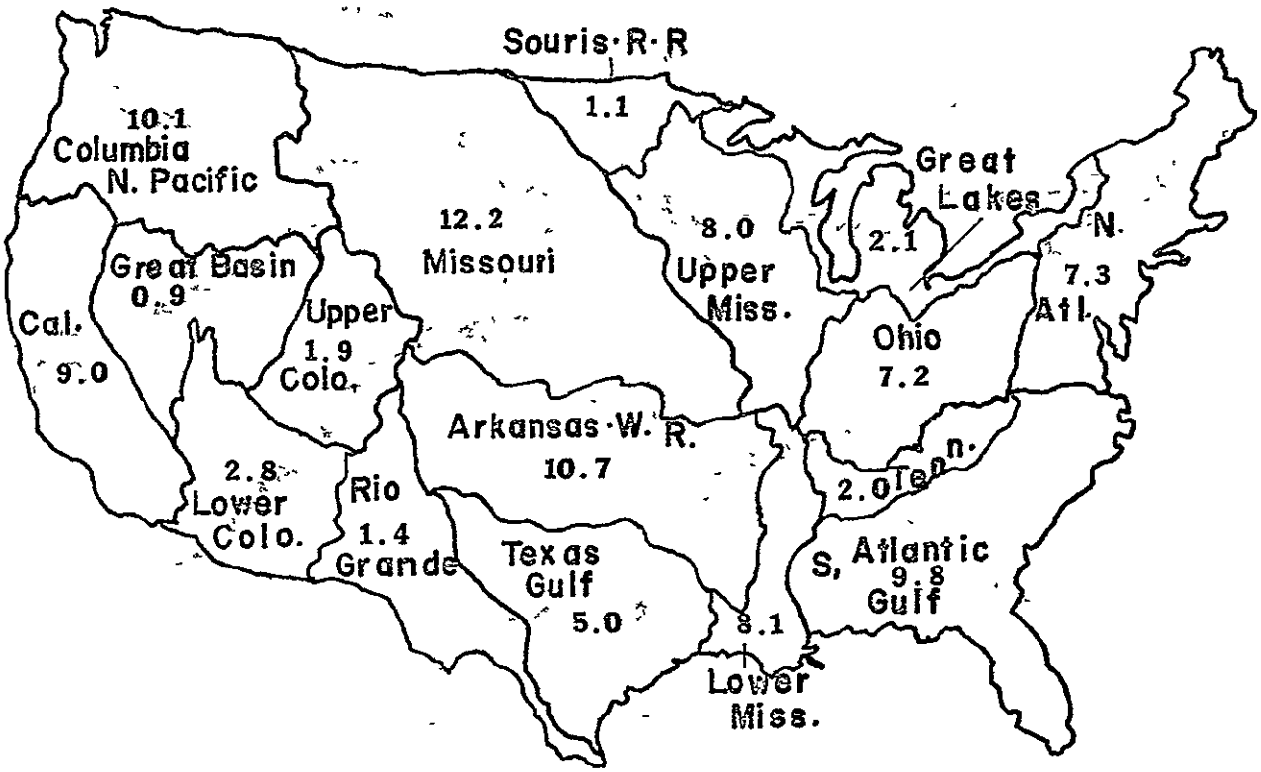
TYPICAL FLOOD PLAIN · 50 year recurrence



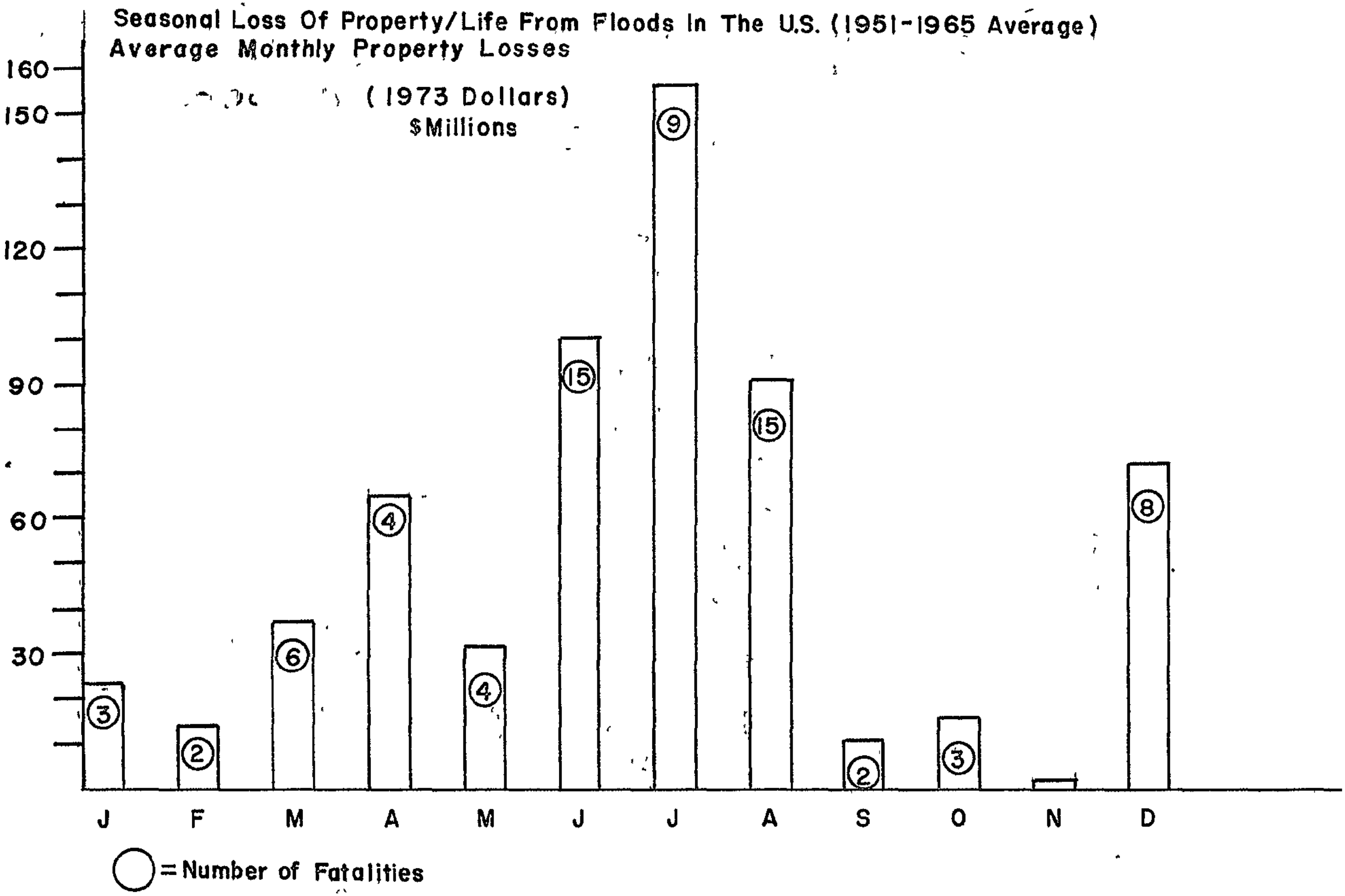
Flood damage is a function of the flood plain area, of the height reached by floodwaters, and of the value of economic producing units and infrastructures within the flood plain.

It can be seen that the economic return of flood mitigation varies significantly among the geographic areas of the U.S.

Distribution of flood damage- Total U.S.=100%



Floods are stochastic phenomena with seasonal trends. Each region displays its own seasonal trends. Knowledge of temporal trends is important to schedule flood damage abatement efforts and concomitant data-gathering activities.


Seasonal Loss Of Property/Life From Floods In The U.S. (1951-1965 Average)
Average Monthly Property Losses
(1973 Dollars)
$Millions
160
150
120
90
60
30
3
2
6
4
4
15
9
15
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8
J
F
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J
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= Number of Fatalities

It is not economically practical to totally eliminate flood damage.

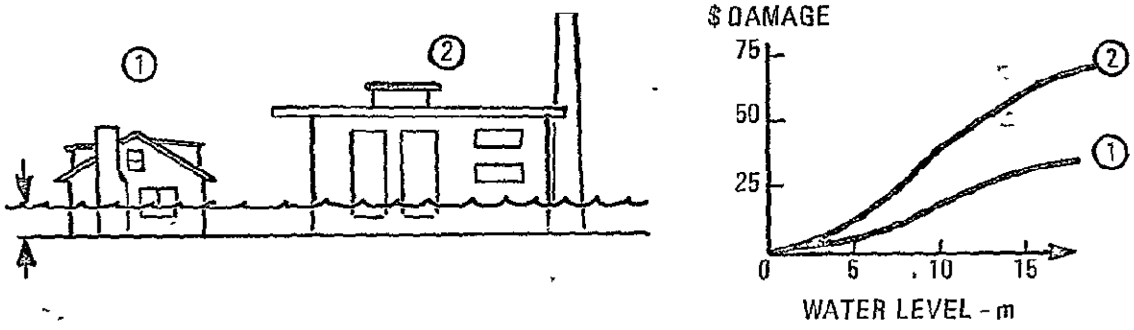
The reason is that floods are statistical phenomena: there is always a chance of a flood event exceeding the capacity of any flood-containment system.

The cost of remedial measures must be commensurate with the reduction of damage they bring about.

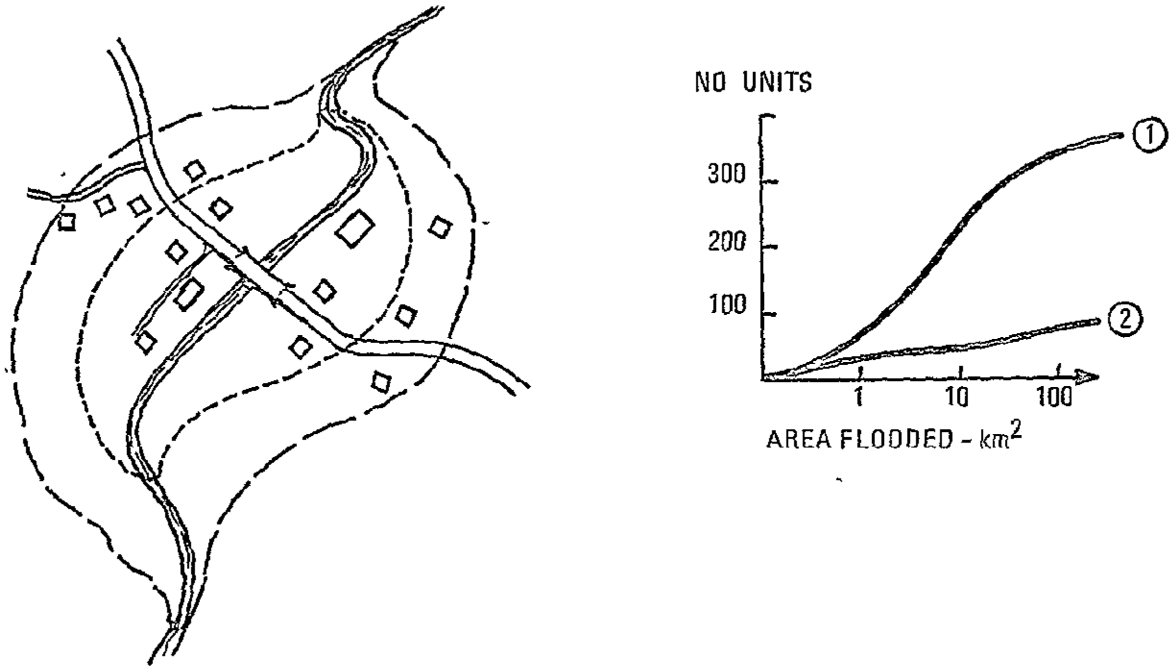
The key criteria of flood management is, therefore, benefit/cost.

The damage model first relates the water level to the damage accruing to typical economic units -- dwellings, industrial plants, crops and infrastructures.

Next, it relates the area flooded, and water level, to the number of economic units within it.



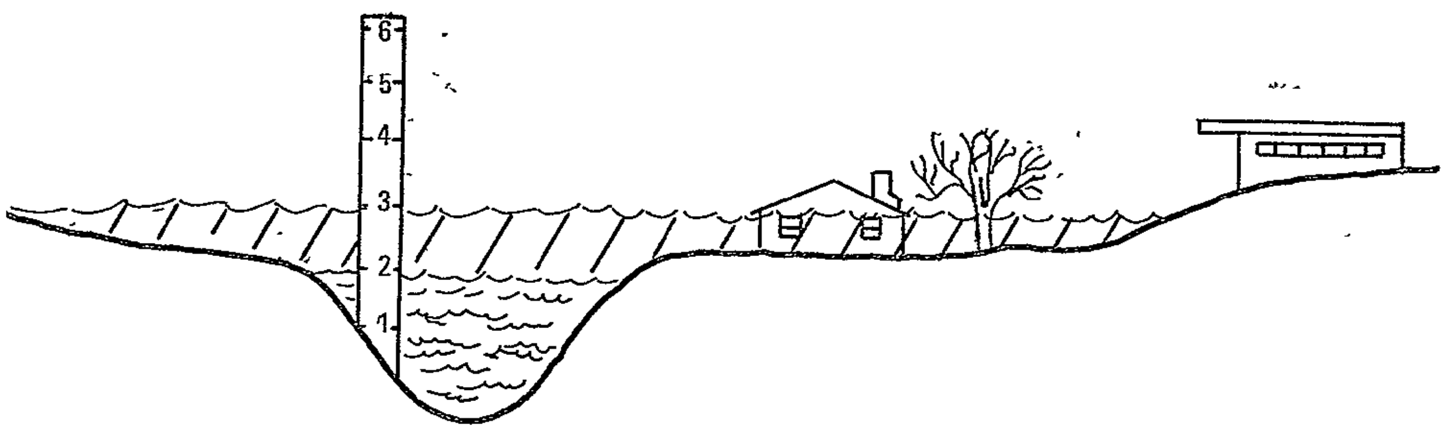
WATER-LEVEL ⟶ UNIT DAMAGE



AREA FLOODED ⟶ NO. OF UNITS

COMPONENTS OF THE DAMAGE MODEL

The total damage is then related to the stage height, i.e., the water level in the watercourse.



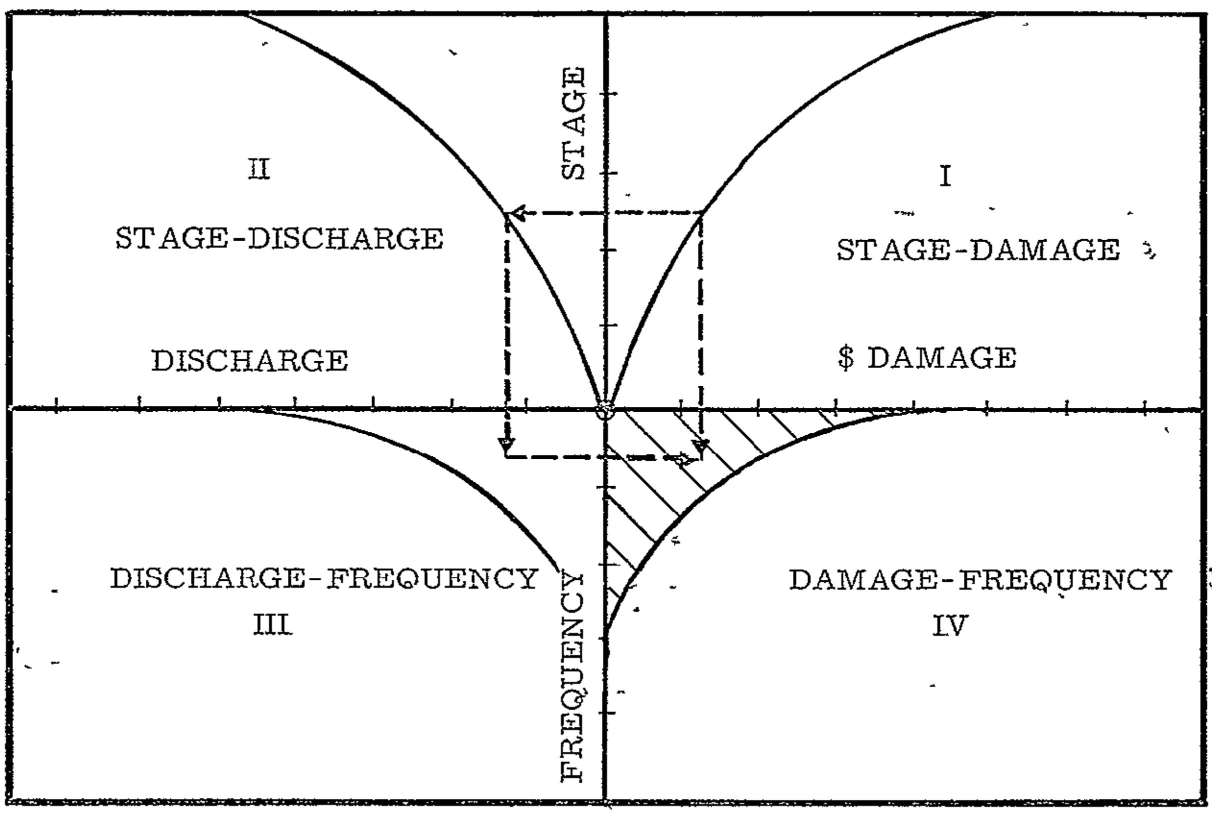
AREA FLOODED

STAGE → WATERLEVEL → TOTAL DAMAGE

The stage height relates to runoff -- also known as discharge.

The next important point is how often in time will a given runoff be achieved. This is the discharge-frequency relationship. Once these relationships are measured or calculated, the extent of economic damage can be related to how often will the damage occur. In particular, it can be related to the average yearly damage, which is the area under the Damage-Frequency Curve (Curve IV). This area obviously represents the maximum annual benefits achievable from flood damage reduction.

RELATIONSHIPS BETWEEN HYDROLOGIC AND DAMAGE QUANTITIES



The techniques for reducing flood damage vary from ad-hoc methods and procedures, employed only when a flood is impending, to policies, and to waterworks of a permanent character.

Evacuation of persons and valuable objects reduces direct damage. Levees confine the flow to within preassigned limits, increasing the stage height permissible before damage occurs.

Channel dredging and improvements increase flow velocity, reducing the water level for a given flow.

Floodproofing techniques confine valuable objects to a dwelling's higher levels and/or specify appropriate techniques for waterproofing.

Retarding basins reduce peak flow by providing a "flywheel", where floodwaters can accumulate.

Controlled reservoirs and bypasses provide a means for modulating the flow; controlled water discharge from a reservoir, prior to a flood, can provide "flywheel" volume for the floodwaters.

Proper land management can reduce the runoff.

Choices between techniques depend upon the value of the expected relief, and the cost of implementing the technique.

METHODS OF FLOOD DAMAGE REDUCTION

TEMPORARY ALLEVIATION

Evacuation

Temporary Levees -- Sandbags

Flooding of less economically significant areas -- Levee blasting

Corrosion Protection - Oil Coating

PERMANENT MITIGATION

Flood Plain Zoning

Removal of Impediments to Flow -- Sediment Dredging, Channelization

Flood Proofing

Alterations to Watershed -- Reforestation

Creation of Retarding Basins

Permanent Control Structures -- Dams, Levees, Water Bypasses

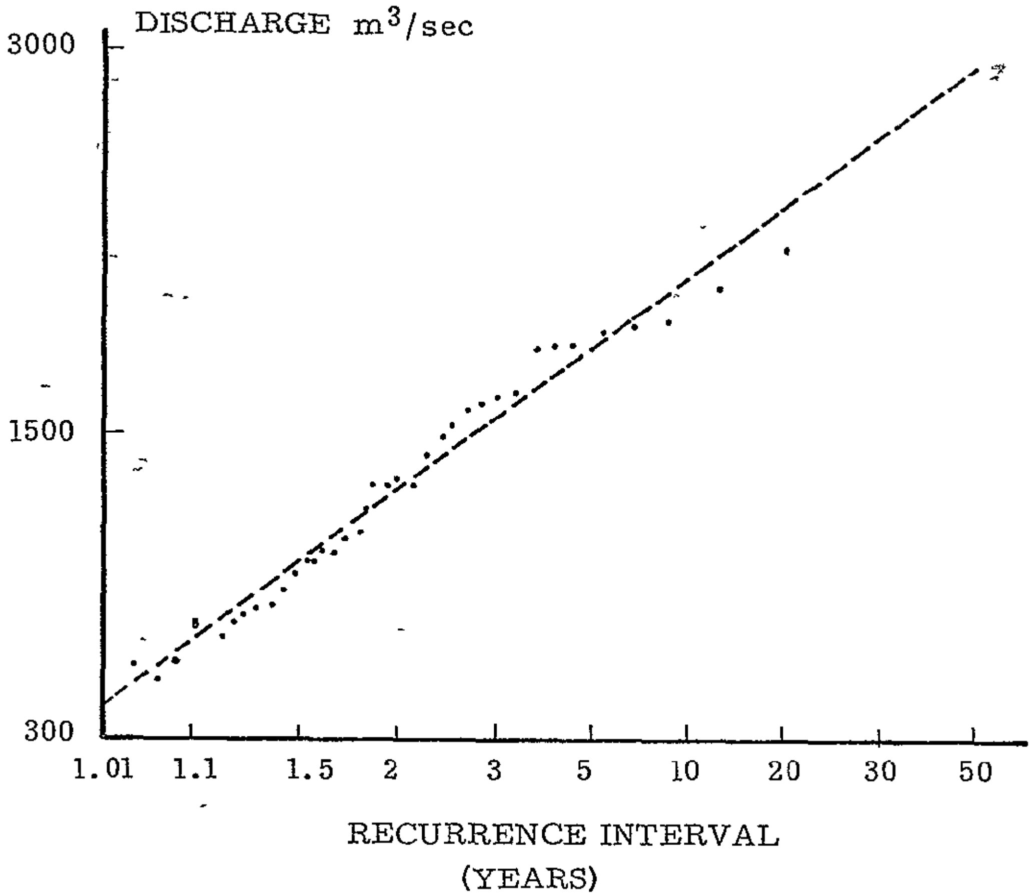
Each flood-damage reduction technique has an associated cost.

The water manager's problem is to achieve proper benefit/cost, i,e., to select the flood-control technique and the size of the flood control works such that the reduction of damage is greater than the cost of the remedial measures.

Since floods are stochastic phenomena, the damage must be defined as the "average damage" over a preassigned period of years.

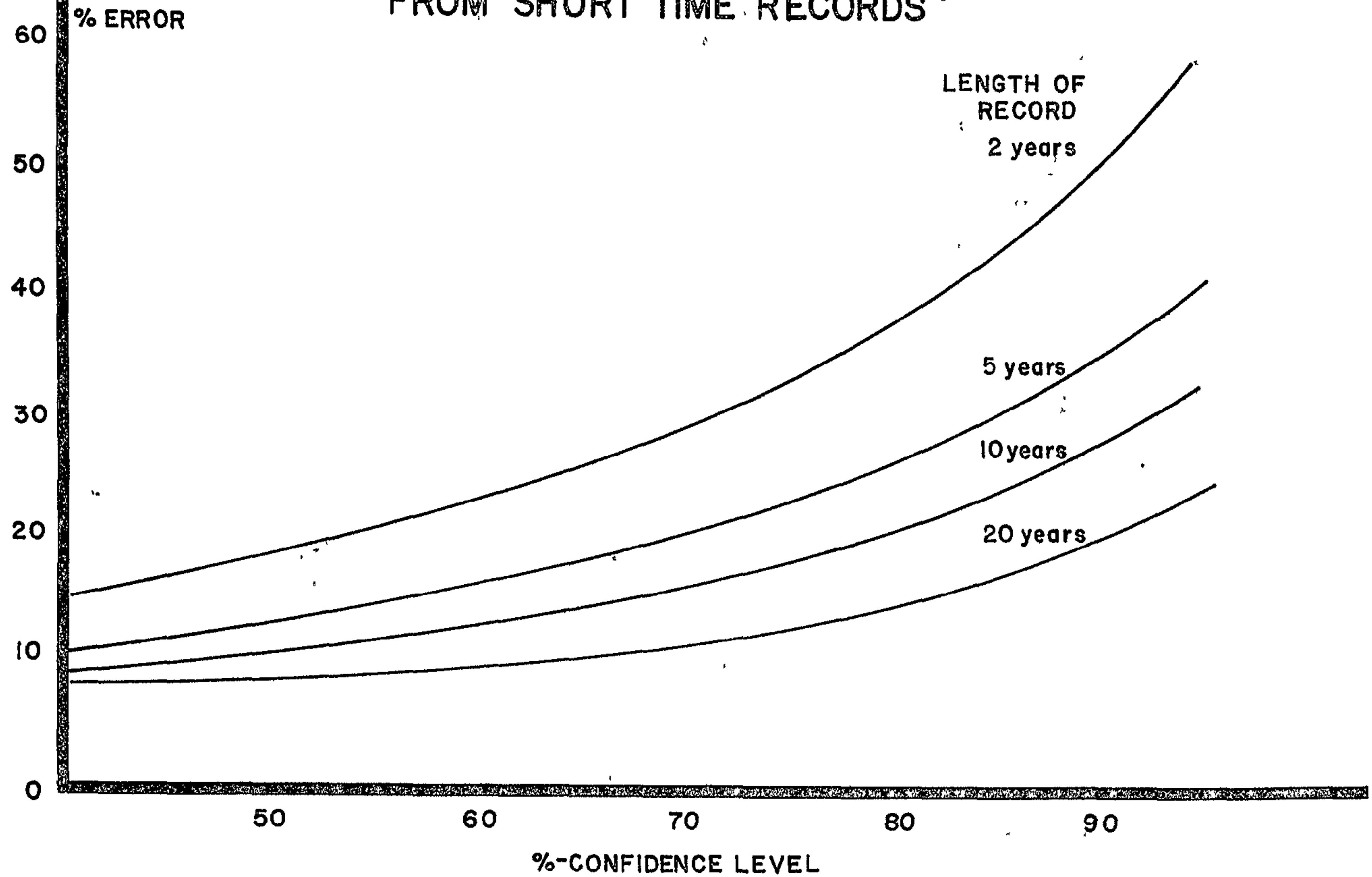
This leads to the concept of "design flood", i.e., the maximum flood that recurs, on the average, within the preassigned or "design" period of time.

TYPICAL FLOW-TIME DISTRIBUTION OF FLOOD



Prediction becomes more reliable the longer the measurement period.

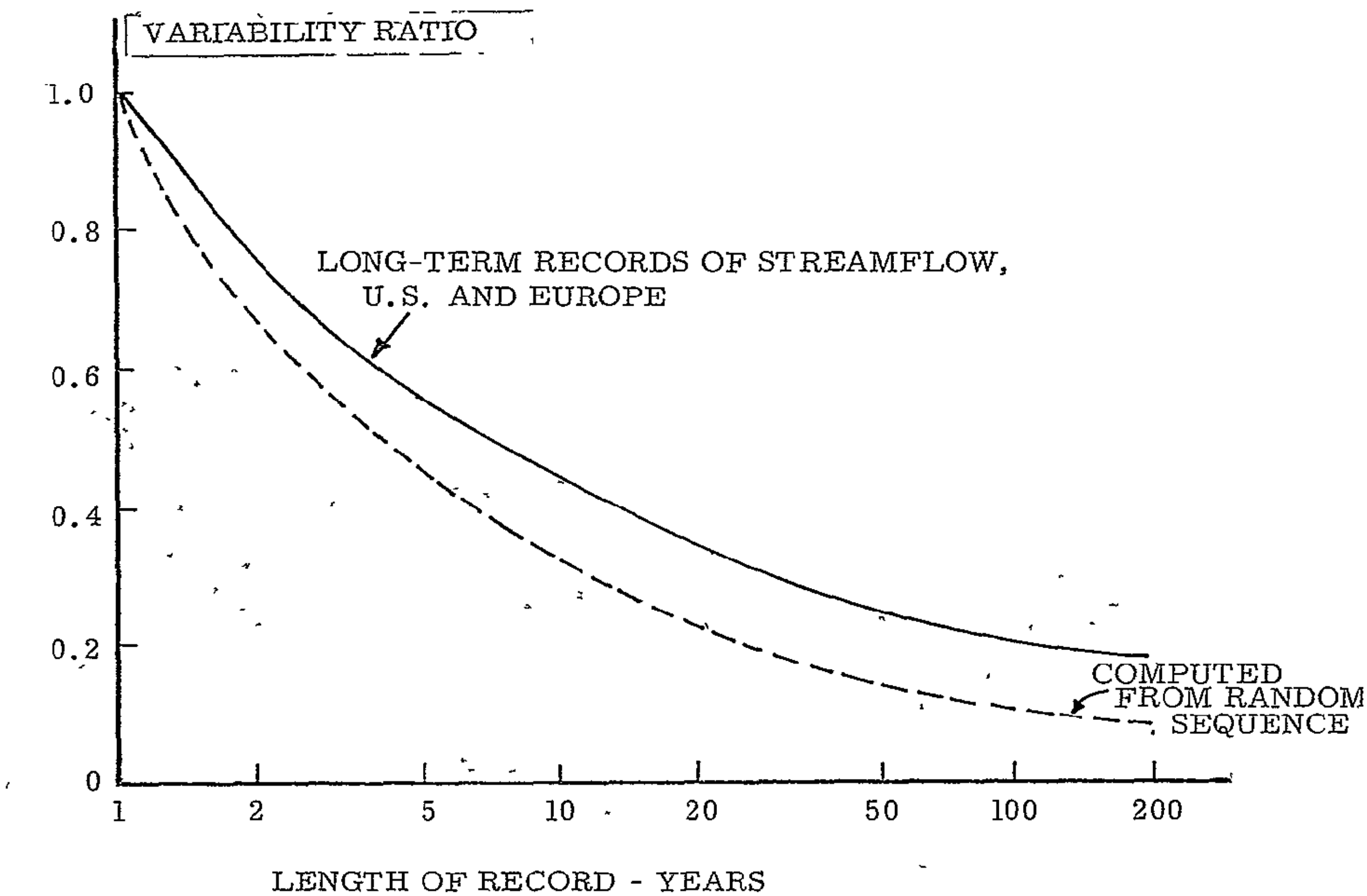
ERROR IN ESTIMATING LONG TIME MEAN RUNOFF FROM SHORT TIME RECORDS



The behavior of flood recurrences is akin to that of random noise. Latest research indicates that the behavior is, however, not completely statistical, but appears to display Markovian-type dependencies.

This further heightens the dependence upon long records.

VARIABILITY OF PREDICTION OF MEAN VALUES
AS AFFECTED BY LENGTH OF STREAMFLOW RECORDS

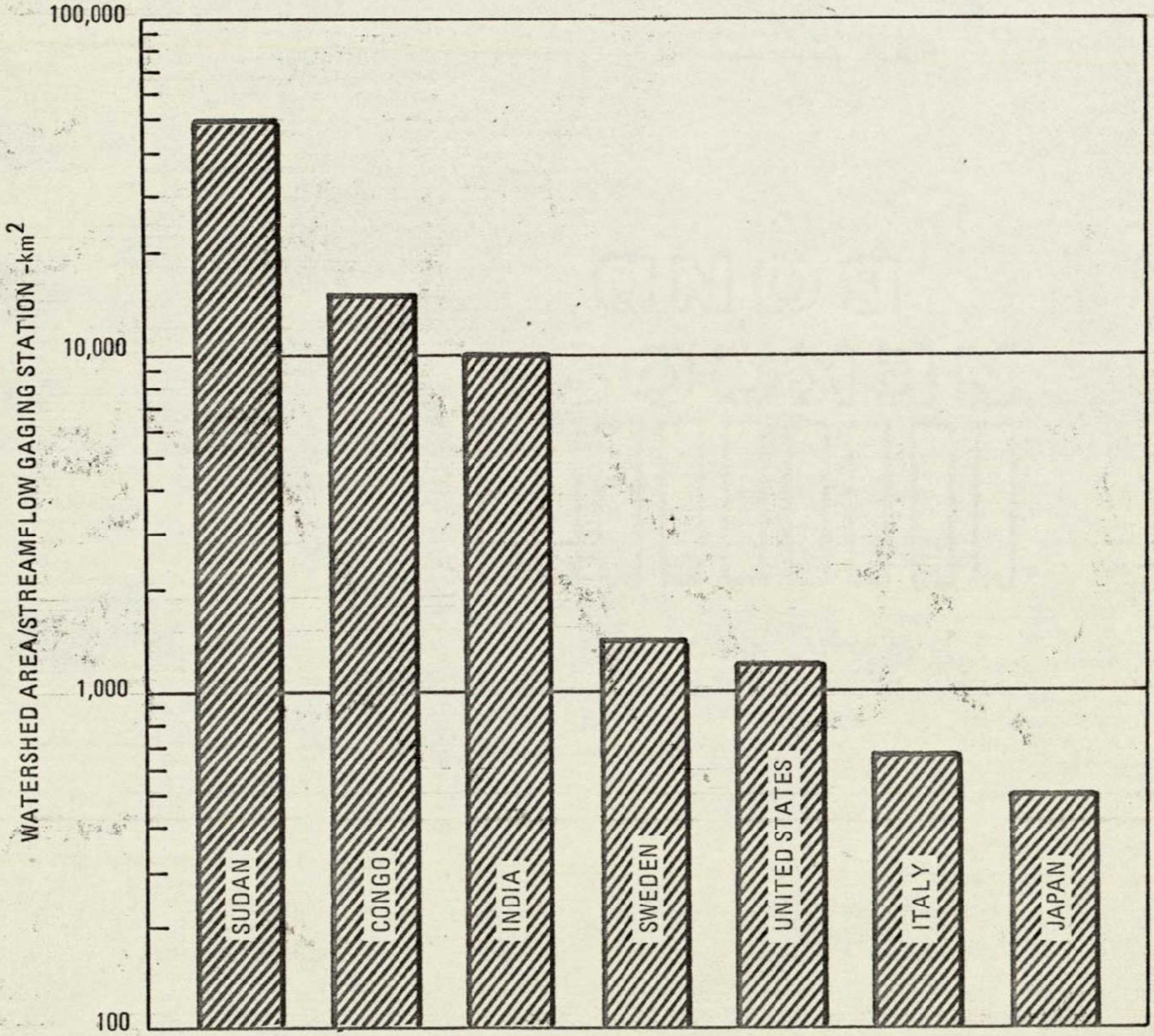


Few watersheds have records longer than 50 years.

Only principal streams from watersheds are instrumented, and then, largely at their output.

The problem is that the flood may not be uniform over the watershed; yet users within subwatersheds also need predictions for proper flood protection.

Average Area of Instrumented Watershed



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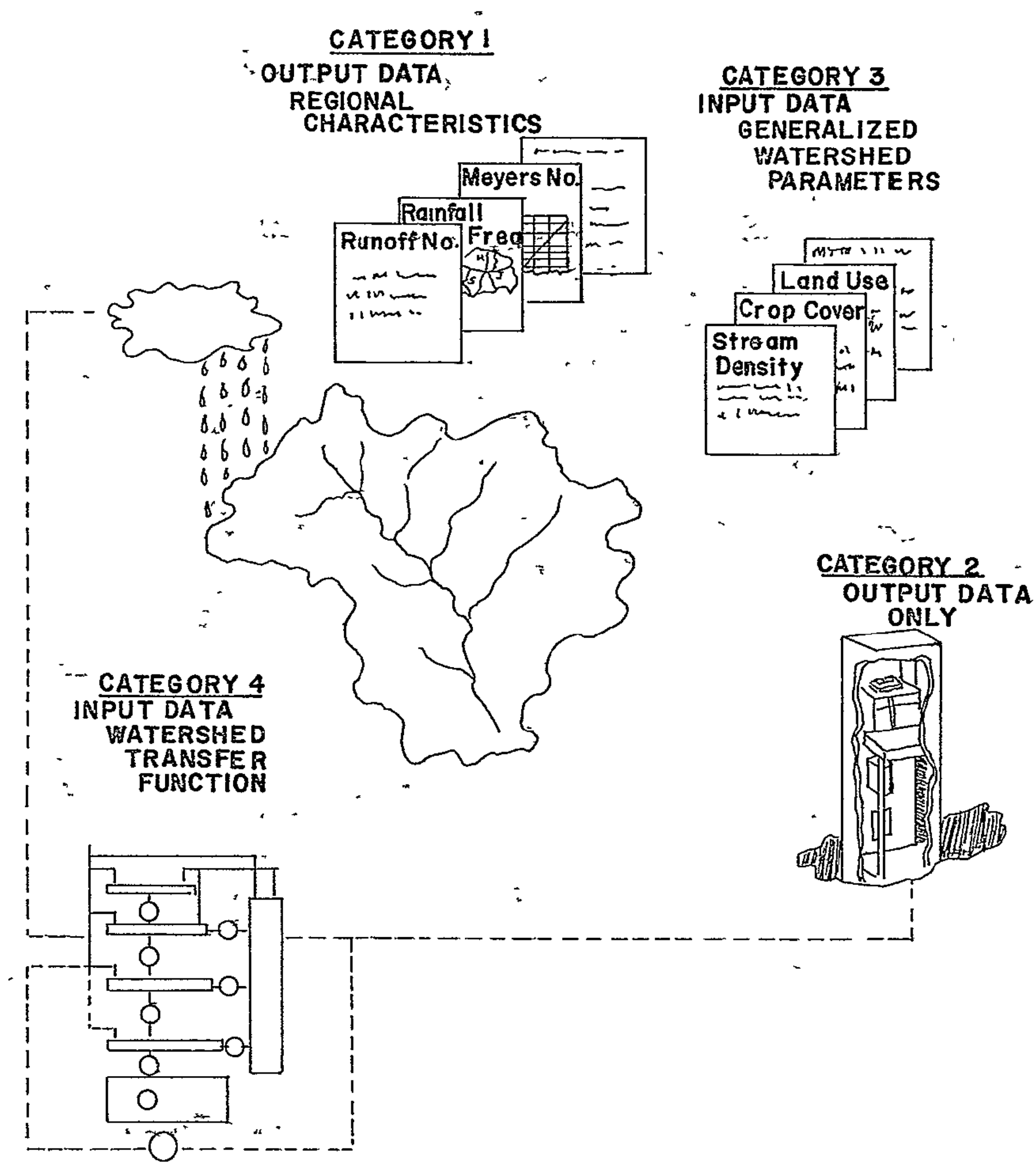
For these reasons, methods have been sought since the early 1900's to estimate design flood from limited measurements.

These fall into four principal categories.


CATEGORY 1
OUTPUT DATA
REGIONAL
CHARACTERISTICS
Meyers No.
Rainfall
Freq
Runoff No.
CATEGORY 3
INPUT DATA
GENERALIZED
WATERSHED
PARAMETERS
Land Use
Crop Cover
Stream
Density
CATEGORY 2
OUTPUT DATA
ONLY
CATEGORY 4
INPUT DATA
WATERSHED
TRANSFER
FUNCTION

Category 1, historically the earliest to appear (early 1900's), seeks to write generalized formulations of the form:

$$q = A^{-n} f(A) g(T) h(W)$$

where

q = flow per unit watershed area, A

T = recurrence interval

W = watershed parameters

f, g, h = functional relationships

n = a numerical coefficient

Over one hundred such formulations have been developed over the years.

MOST EMPLOYED CATEGORY 1 FORMULATIONS

U.S. Fuller: $q = CA^{-0.2}(1+A^{-0.3})(1+0.8\log_{10} T)$

Myers: $q = CA^{-.5}$

MID-EUROPE: $q = CA^{-0.33}$

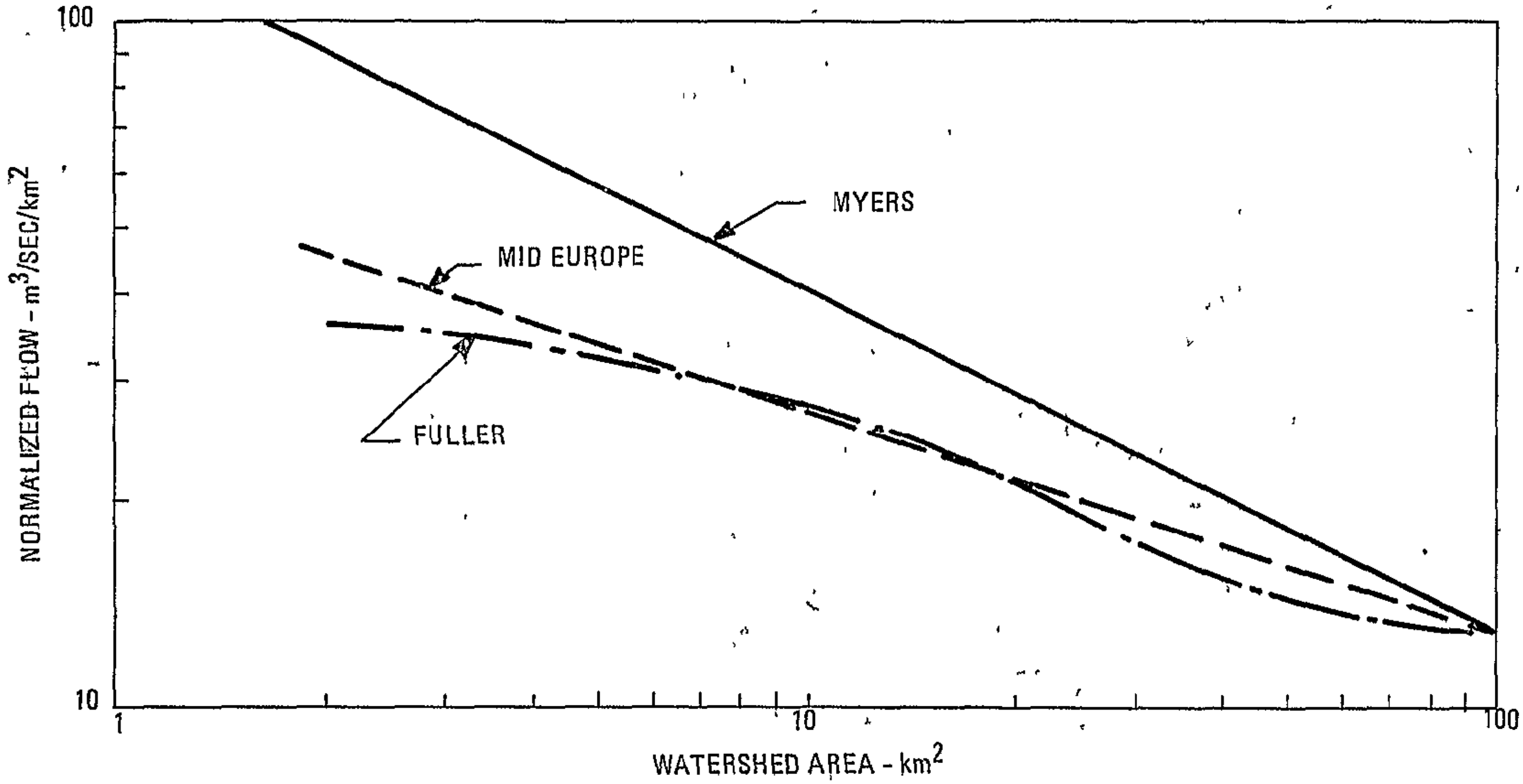
SOUTH EUROPE: $q = CA^{-0.66}$

U.S.S.R.: $q = CA^{-n} g(T)h(w)$

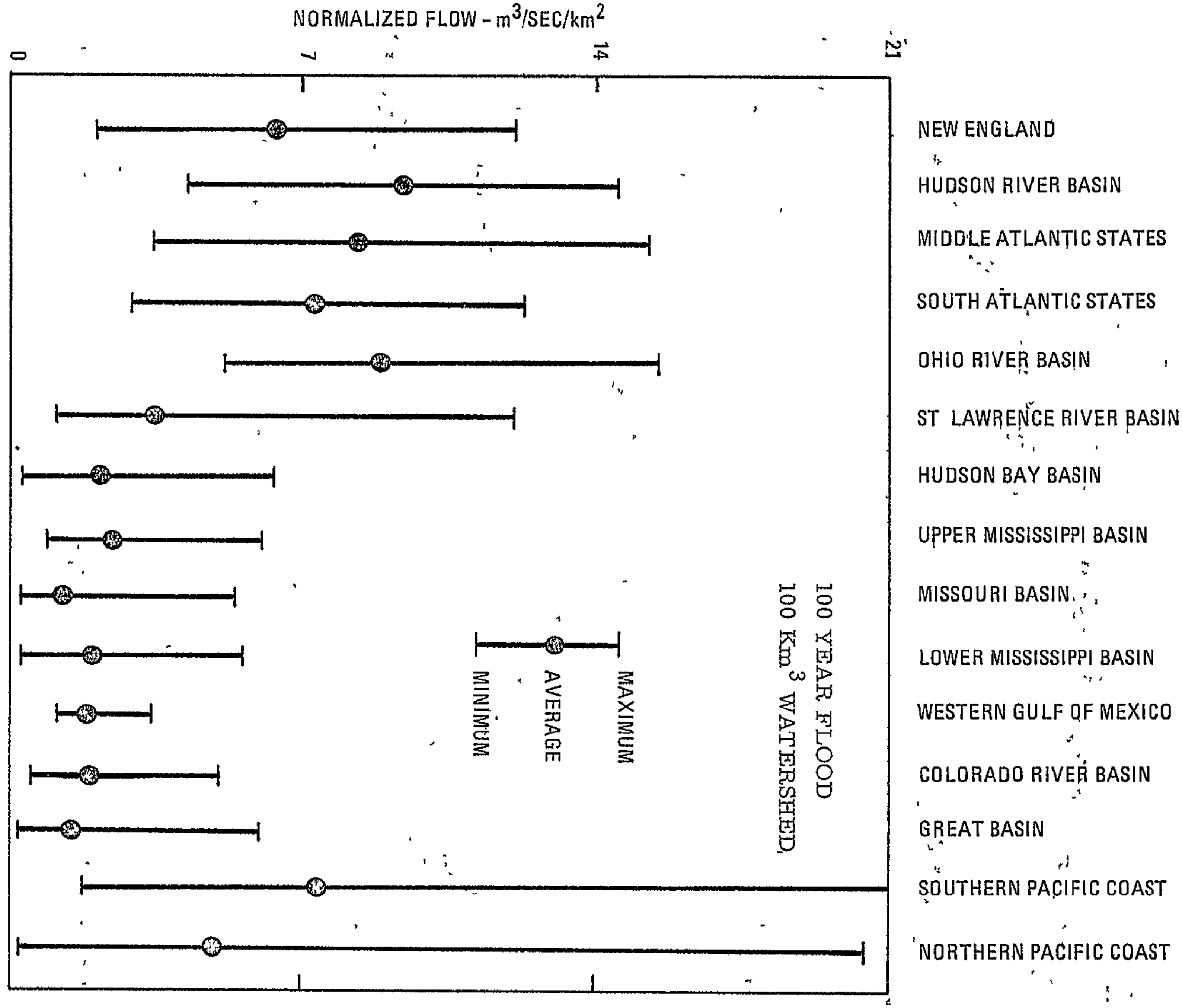
Where the C's are empirically derived constants.

Experience has shown that Category 1 formulations, although still used, are only rule-of-thumb approximations, with far from universal application. More significantly, the extrapolation from the output of a watershed to the outputs of component subwatersheds is unreliable.

DIVERGENCE OF PREDICTION BETWEEN PRINCIPAL CATEGORY - I- EMPIRICAL MODELS



Category 1 formulations also show significant variations when applied to different regions.



REGIONAL VARIATIONS AND INTRAREGIONAL RANGE
OF THE COEFFICIENT IN CATEGORY 1 MODELS

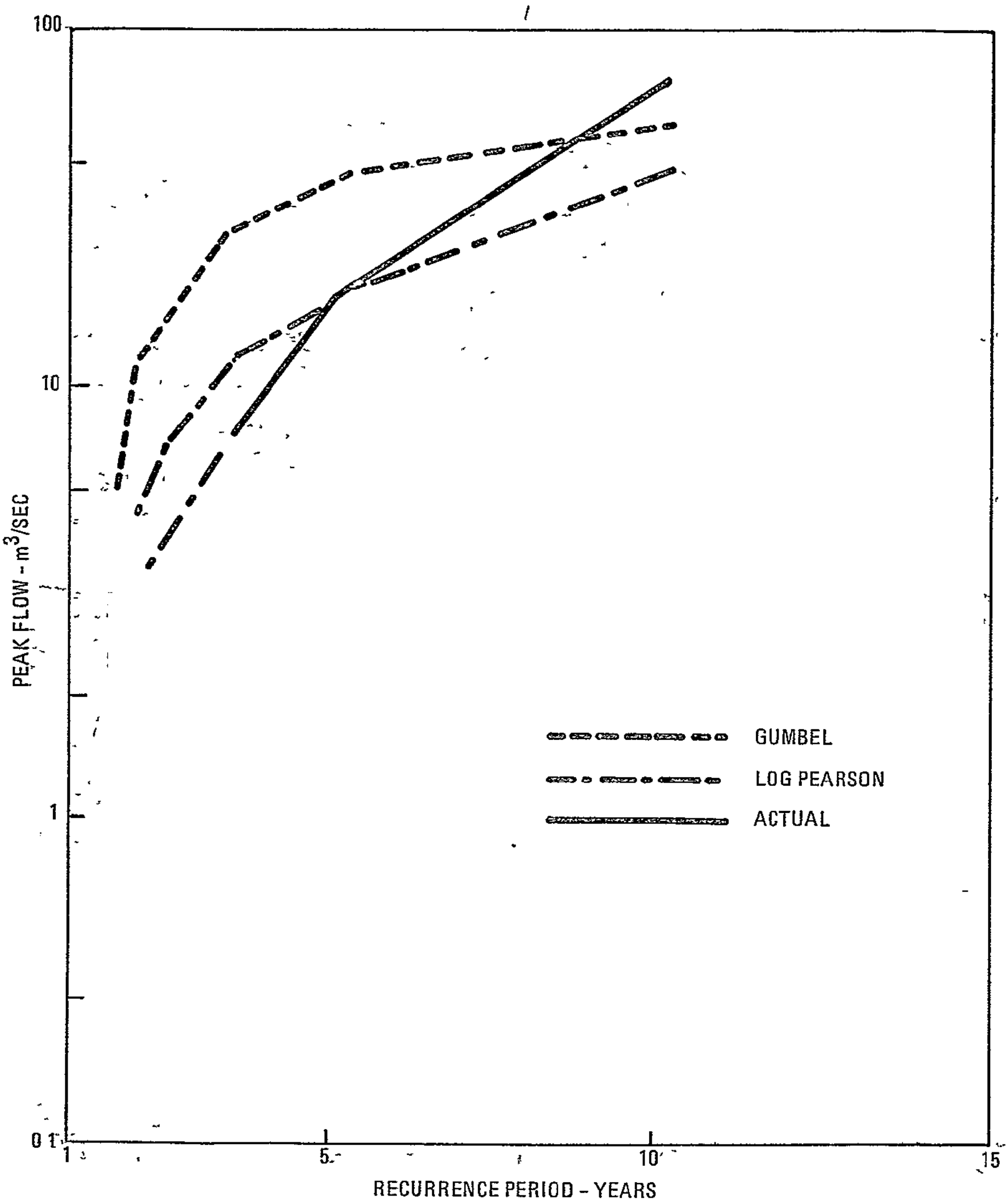
Category 2 methods, first devised circa 1930, consider the flow as a stochastic variable. From measured data, the average standard deviation and other probability functions can be computed.

Sufficient length of record is needed to achieve adequate confidence limits.

In general, the Category 2 design predictions are more reliable than Category 1.

The predictions vary among formulations, as a function of the assumed probability distributions.

They depart from actual flows, in part, because flood events do not appear to follow a truly random distribution. Recent theories, not yet reduced to practice, seem to indicate Markovian-type dependencies between flood events.



DEVIATION OF PREDICTIONS OF THE PRINCIPAL

CATEGORY 2 - STATISTICAL MODELS

Output methods, Categories 1 and 2, suffer from the fact that watersheds vary among themselves, even within the same region. Only adequately long flow records can smooth out the variations.

The input variable, precipitation, is significantly less dependent upon the physiographic characteristics of the land; it is also more densely measured, at lower cost and over longer periods, than streamflow records.

Category 3 methods, initially introduced in the forties, generate formulations which associate precipitation with macrocharacteristics of the watershed.

Category 3 methods are based on formulations of the type:

$$q = A^n i^m g(T) h(W)$$

where

q = flow

i = rain precipitation rate (cm/hr)

T = rain recurrence interval

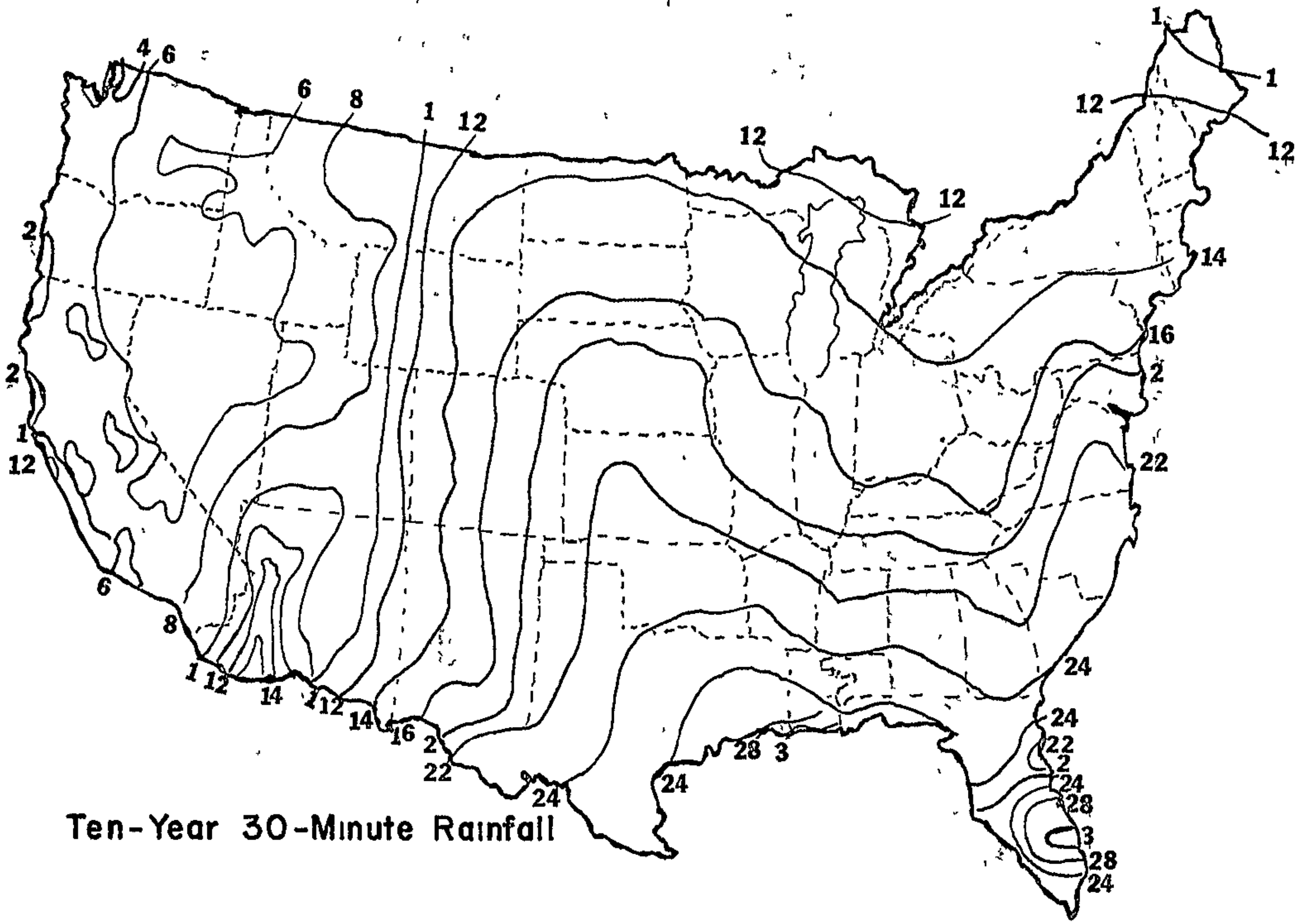
W = watershed parameters

g, h = functional relationships

A = watershed area

n, m = numerical coefficients

RAINFALL RECURRENCE DATA



Ten-Year 30-Minute Rainfall

WIDELY EMPLOYED CATEGORY 3 FORMULATIONS

U.S.: "Rational Formula" $q = A\, i\, h(W)$

Soil Conservation Service: $q = A\, i\, h'\,(W)$

UK: Rodda Formula $q = CA^{0.77}\, i^{2.92}\, D^{.81}$

Where D = Drainage Density =

= Stream Length/Area

h and h', in the previous formulas, are functions of ground cover, subsoil permeability, relief, averaged over the watershed, and then adjusted regionally.

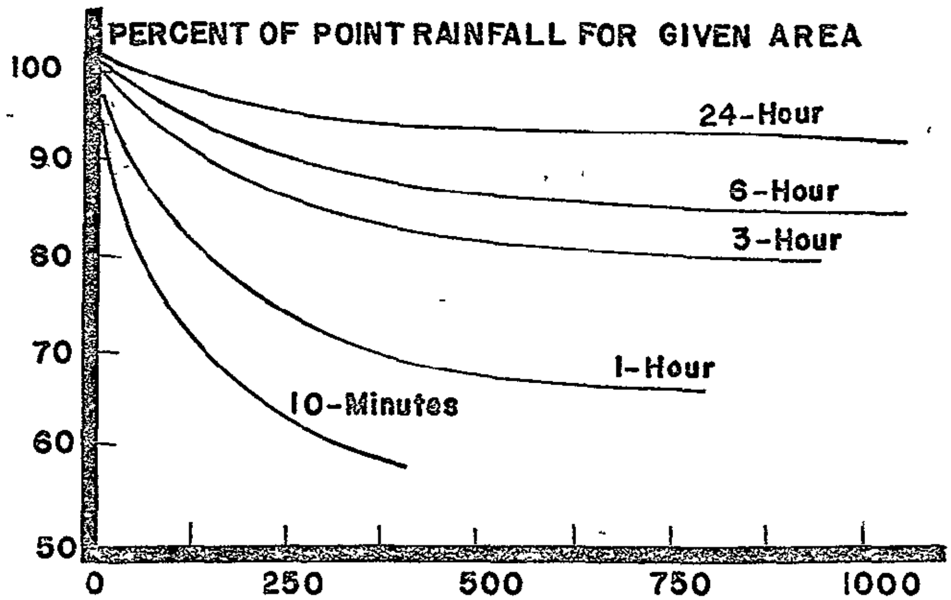
VALUES OF f (h) USED IN THE RATIONAL FORMULA

Soil Type	Cover: Cultivated	Pasture	Woodland
Sand, Gravel	0.2	0.15	0.10
Clay, Loam	0.4	0.35	0.30
Shallow Soil Above Bedrock	0.5	0.45	0.40

The errors of Category 3 formulations increase with size of watershed due to non-uniformity of rain.

These formulations are thus generally restricted to watersheds not exceeding areas of order 100 square kilometers.

VARIATION OF RAINFALL WITH AREA



For large watershed areas, displaying significant physiographic variations, accurate predictions require a more detailed description of the watershed than is afforded by integrated formulations.

Category 4 formulations seek to correlate precipitation events with watershed output flow through a "watershed transfer function". The transfer function is derived from a set of mathematical equations which describe the phenomena governing the watershed's hydrologic regime.

PRINCIPAL CATEGORY 4 METHODS IN USE IN THE U.S.

- Unit Hydrograph
- Synthetic Hydrograph
- API - Continous
- Streamflow Regulation and Reservoir Regulation Model
- Sacramento Model
- Stanford Model
- SCS - TR20
- HEC
- USDAHL

The four hierarchies of flood management:

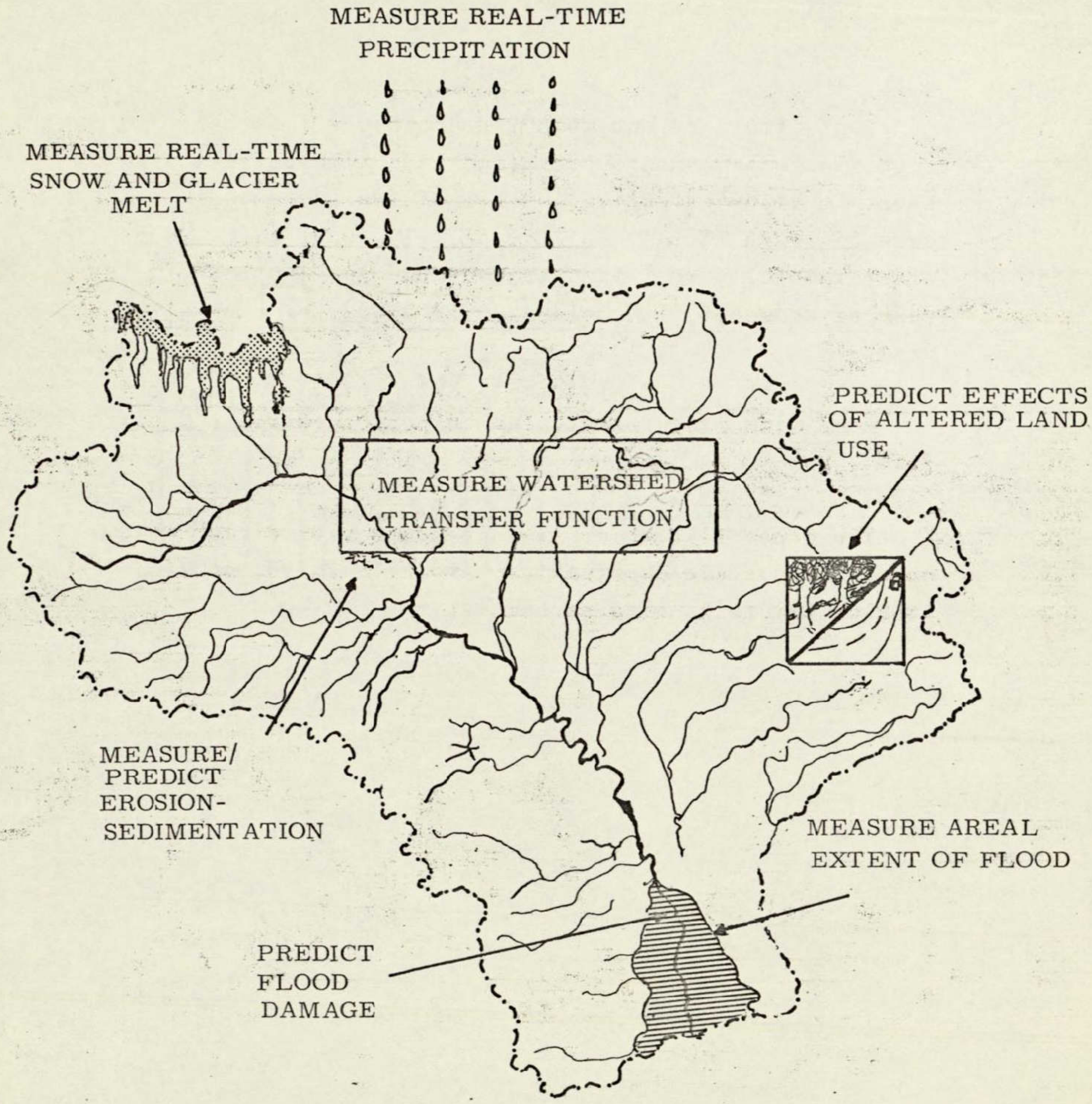
1. FLOOD WARNING - timely alert to minimize losses of life and property.

2. FLOOD DAMAGE REDUCTION - selection of technique and implementation of waterworks, plus dynamic control system.

3. MULTIPLE USE - flood mitigation plus optimization of supply schedule to match user demand schedule.

4. LAND USE MANAGEMENT - prediction of the effects of watershed's natural or man-induced alterations.

The accomplishment of these objectives hinges upon accomplishment of seven principal tasks.



PROGRAM MAJOR TASKS

Real-time does not mean "instantaneous"; rather, it signifies measurements performed in a time sufficiently short to allow effective control of the system. In the case of flash floods, which typically occur a few hours after rainfall, real-time is reckoned in minutes. In the case of snowmelt, it could signify hours, or even a few days.

Real-time measurements can be performed via DCS platforms.

The other five major tasks possess significant components of surface observables, amenable to the application of Remote Sensing techniques.

POTENTIAL CONTRIBUTIONS OF REMOTE SENSING

TO

FLOOD DAMAGE ALLEVIATION

Cost Reduction Over Conventional Methods

- Flood extent measurement
- Watershed characteristics

Innovation Over Conventional Methods

- Economic model of flood damage
- Watershed transfer function
- Real-time precipitation measurement
- Prediction of effects of altered land use
- Erosion-sedimentation model

3. WATER RESOURCE SUPPLY AND DEMAND

3.1 CURRENT AND FORECASTED OVERALL AVAILABILITY AND REQUIREMENTS

In defining water usage, distinction must be made between withdrawal and consumption.

Withdrawal is the total amount taken in by an activity. Withdrawn water may be returned to the water supply and be available for further use by the same or another activity. Consumed water is that which is not usefully returned. It is evaporated or incorporated in a product.

For example, industrial cooling water can be returned almost entirely to the source, a large fraction of irrigation water is lost through evaporation.

For irrigation and large waterworks projects, the acre-foot unit is most commonly used to measure volume of water. Metered water for industrial, household, and municipal use is commonly measured in units of K gal (thousand gallon), or in K cu. ft. (thousand cubic feet).

Most employed unit of flow for large projects is the mgd (mega gallons per day). The units employed abroad, and increasingly being introduced in the U.S., are cubic meter and cubic meter/second.

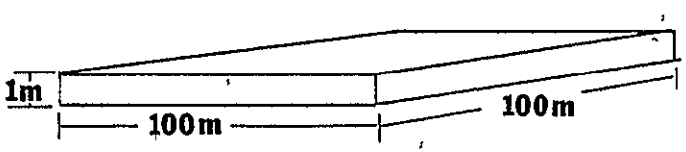
DEFINITIONS AND MOST COMMONLY EMPLOYED UNITS

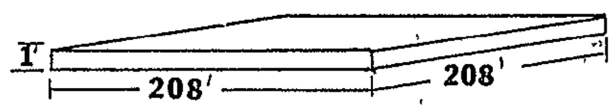
WITHDRAWAL: VOLUME OF WATER TAKEN IN

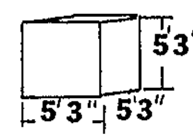
CONSUMPTION: PORTION OF INTAKE VOLUME WHICH IS DISSIPATED

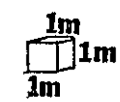
MASS UNITS

1 Hectare-meter (ha-m) → 8.3 Acre-feet (AF) 1AF → 300 K gal. 1 K gal. → $4m^3$









FLOW UNITS

1 mega-gallon per day (mgd) → 4,000 m^3/ day → 0.046m^3/second

(5,000 households)

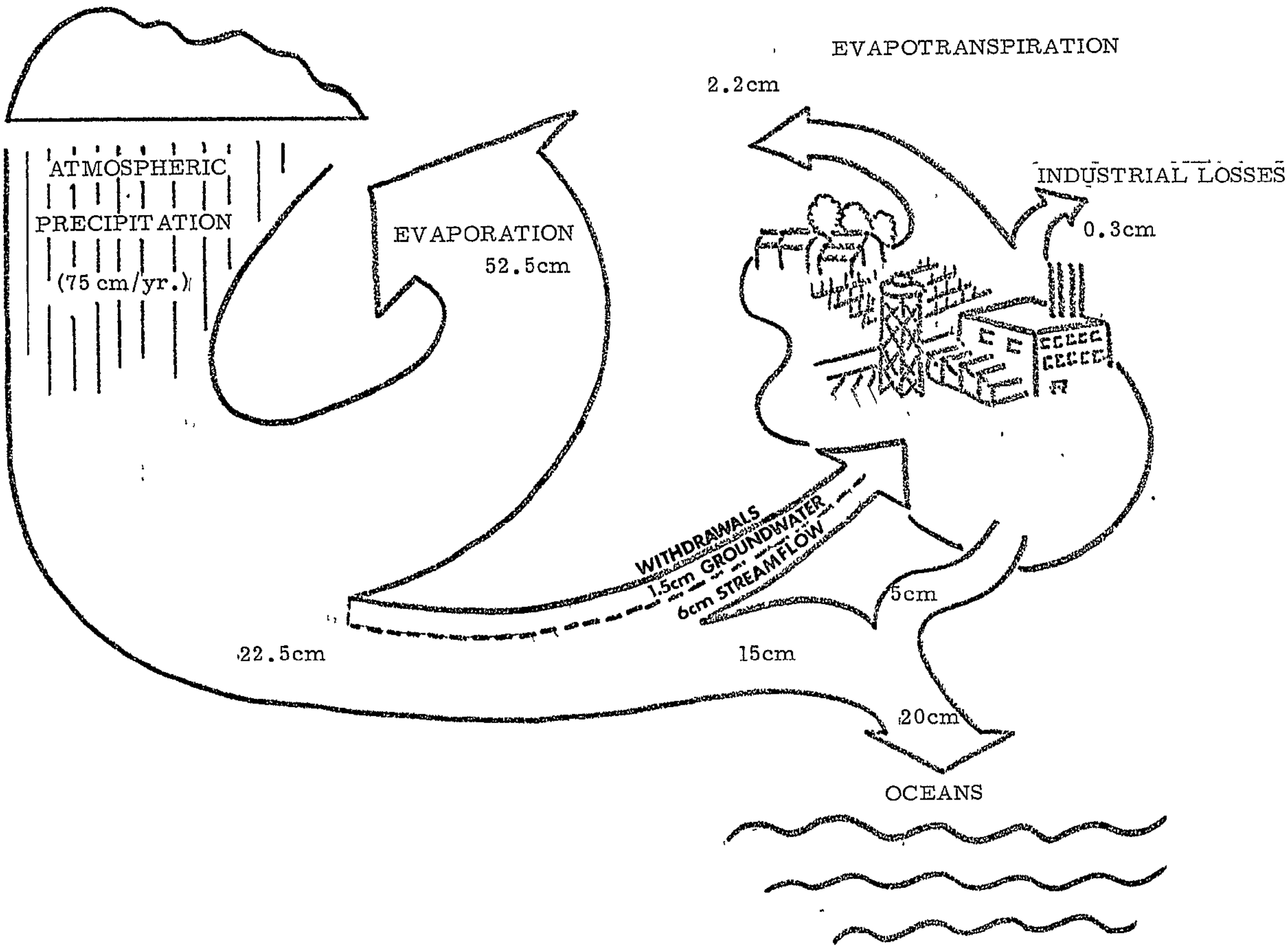
1 m^3/ second → 21.6 mgd

Practically all the fresh water supply is generated by precipitation. In the U.S., 70% of this input is lost through evaporation and evapotranspiration before reaching exploitable concentrations.

Of the remaining 30%, which goes into streamflow and to replenish groundwater supplies, one third is withdrawn by human activities. A little over 40% of this is consumed.

Thus, the efficiency of utilization of the supply in terms of withdrawals is 10%: in terms of net use, 7%.

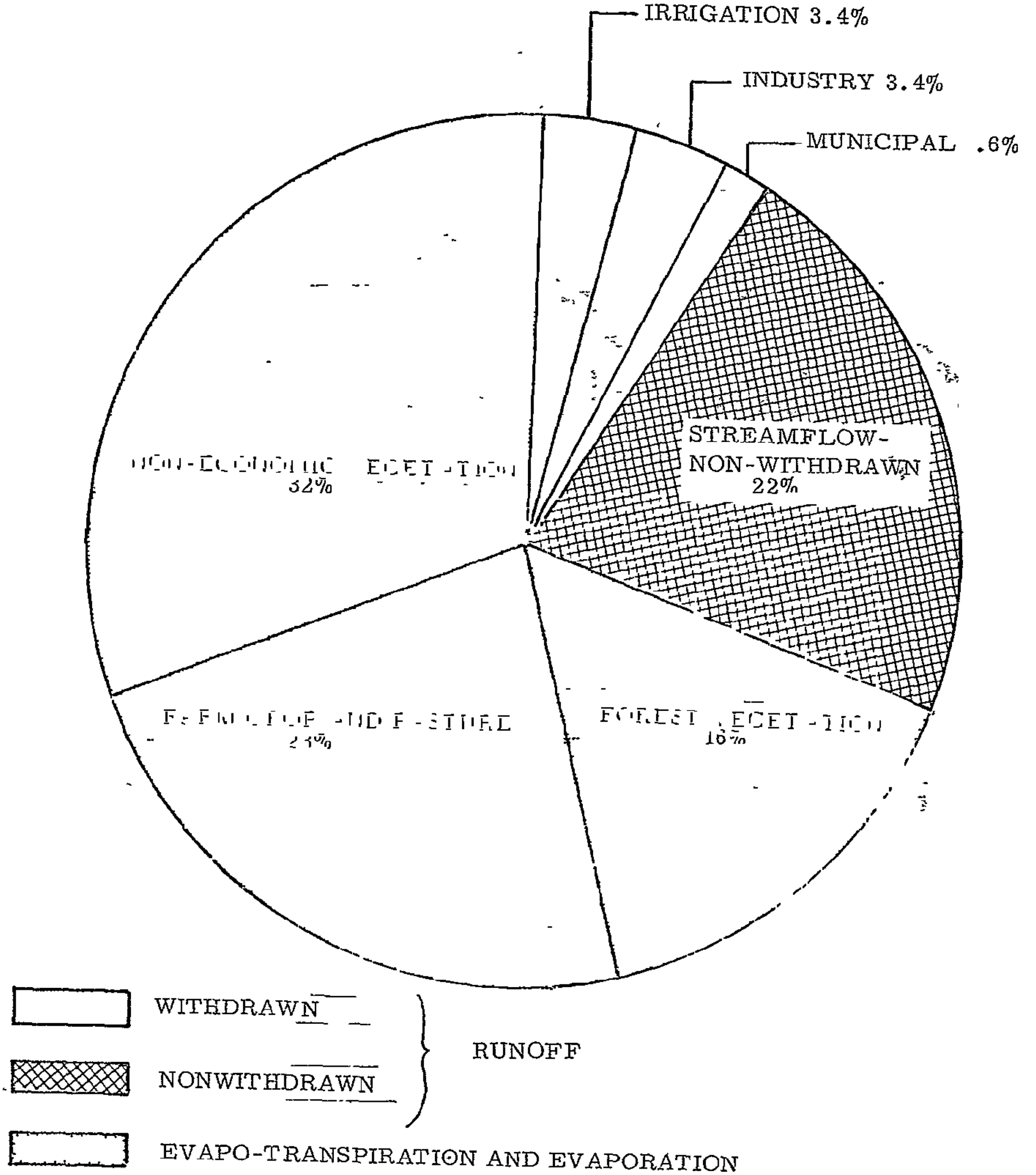
SUPPLY AND DEMAND OF WATER - U.S.



The majority, approximately 92% in 1970, of the fresh water withdrawn is utilized in equal parts by agricultural and industrial activities.

Urban and household use accounts for only 8% of withdrawals.

ALLOCATION OF WATER DEMAND (1970)

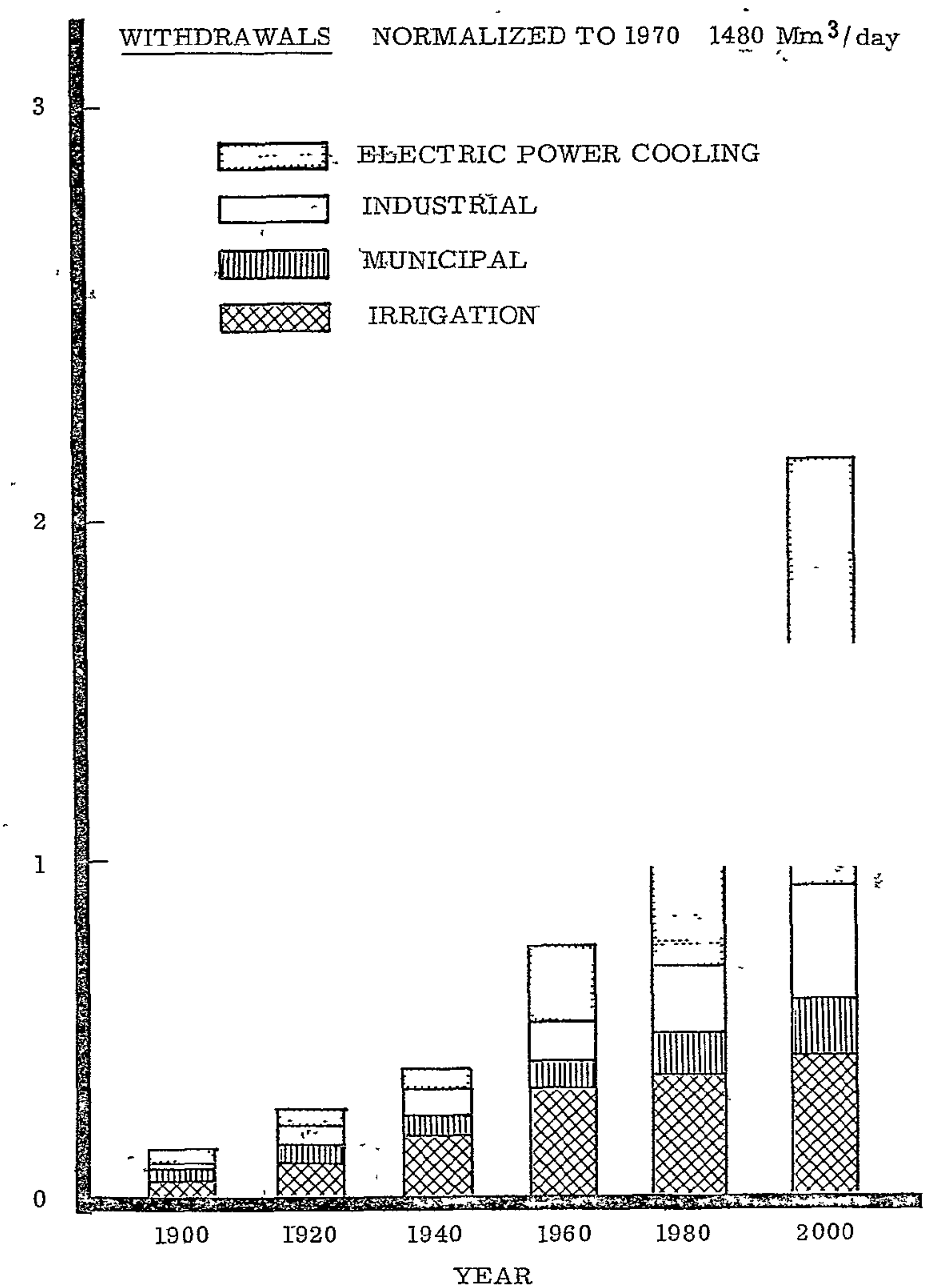


TOTAL SUPPLY : 5700 km^3/yr 570 Million ha-m

The industrial sector is expected to account for the major future growth in fresh water withdrawals due to the cooling requirements imposed by the growing demand of electrical energy.

Note that these forecasts are based upon extrapolations of historical trends of population growth and per capita demand increases. They do not reflect potential slow-downs in demand caused by demographic or resources crises.

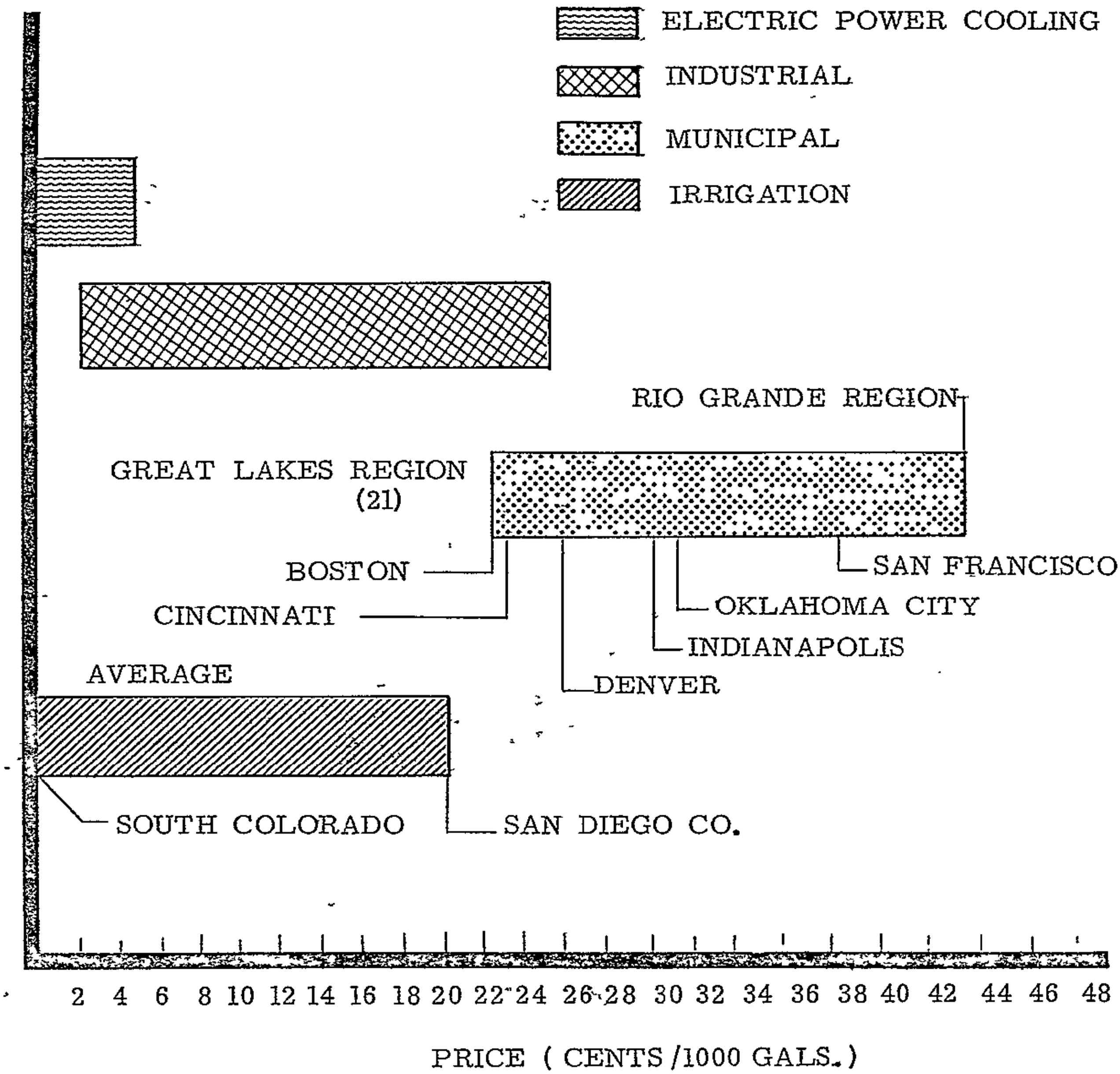
GROWTH OF U.S. WATER DEMAND



The economics of water incorporate combinations of free market and social pricing policies. In many applications, consideration of social value overshadow those of return on investment.

The price of water, therefore, varies rather widely over the U.S. and among sectors of utilization.

PRICE OF WATER U.S. 1970

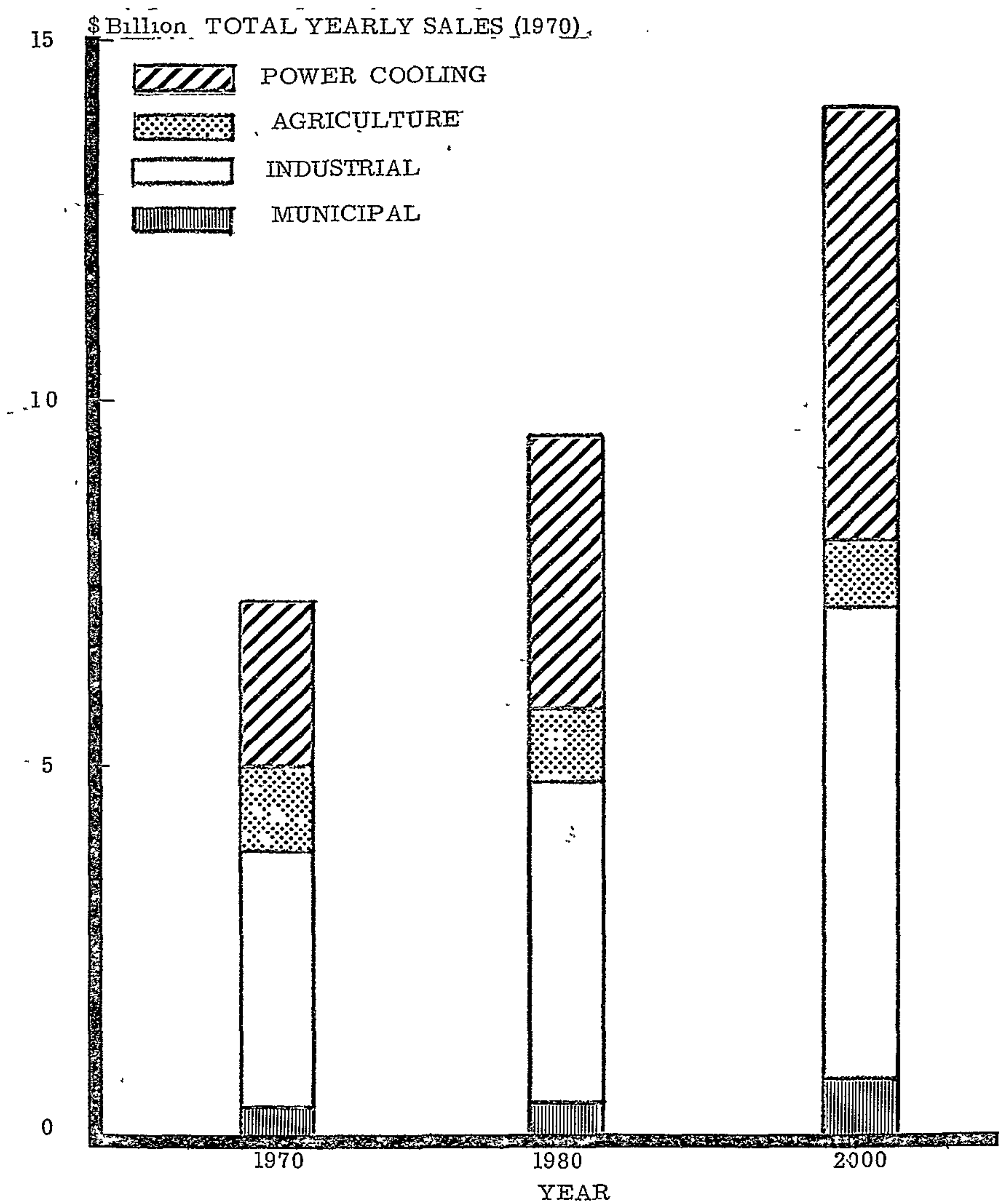


The total price paid for fresh water used by human activities in the U.S. is of order $10 billion in 1973, at 1973 prices.

The worth of this water, expressed by the prices that would be paid in a truly free market, is considerably higher. Good estimates of this true worth are not available.

The forecasted growth in water "revenue" does not take into account price increases potentially induced by scarcities in certain U.S. regions.

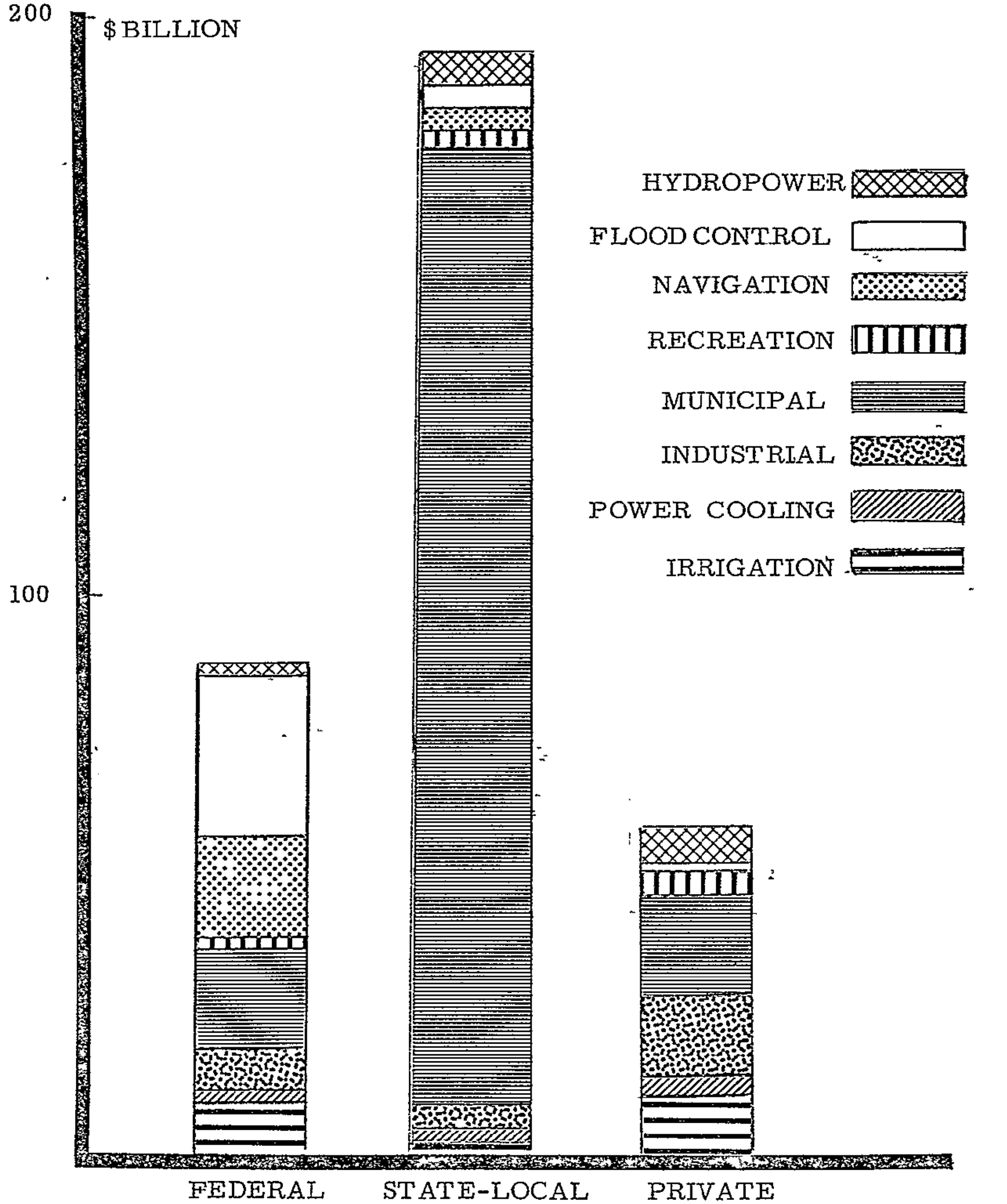
THE U.S. WATER BUSINESS



Total investments in waterworks from the beginning of U.S. history are of the same order of magnitude as the national debt.

These investments are reckoned in current dollars, i.e., the dollar's value at the time it was spent. In terms of 1970 dollars, the figure would be at least 50% higher.

U.S. INVESTMENTS IN WATER RESOURCES UP TO 1970

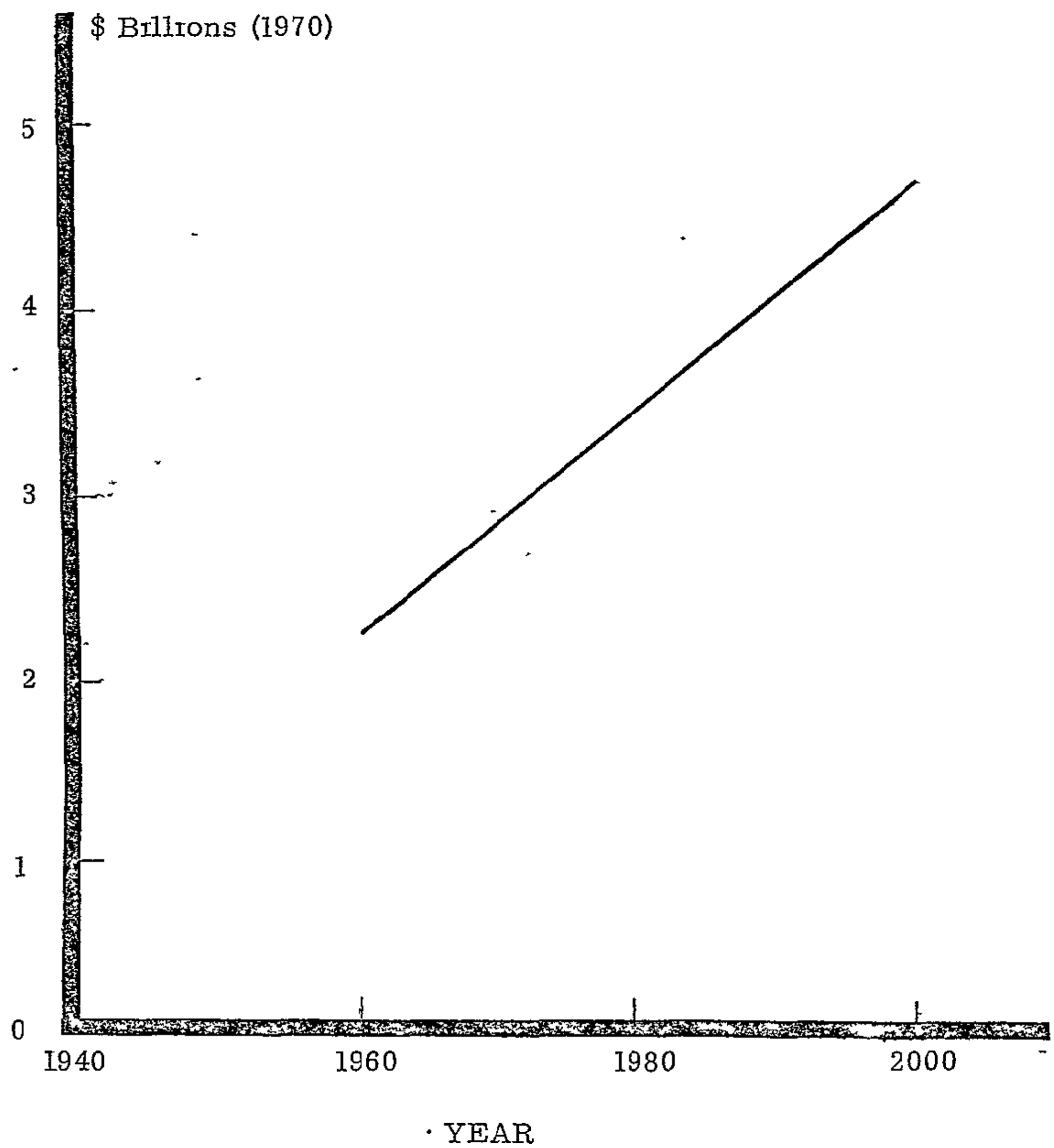


Yearly expenditures for waterworks, now of order \$2.5 billion, will at least double by 2000 A.D.

The forecast does not take into account potential acceleration caused by water scarcity in certain U.S. regions, nor does it include the increased cost of cooling installations for electric energy generation plants induced by conservationist pressures.

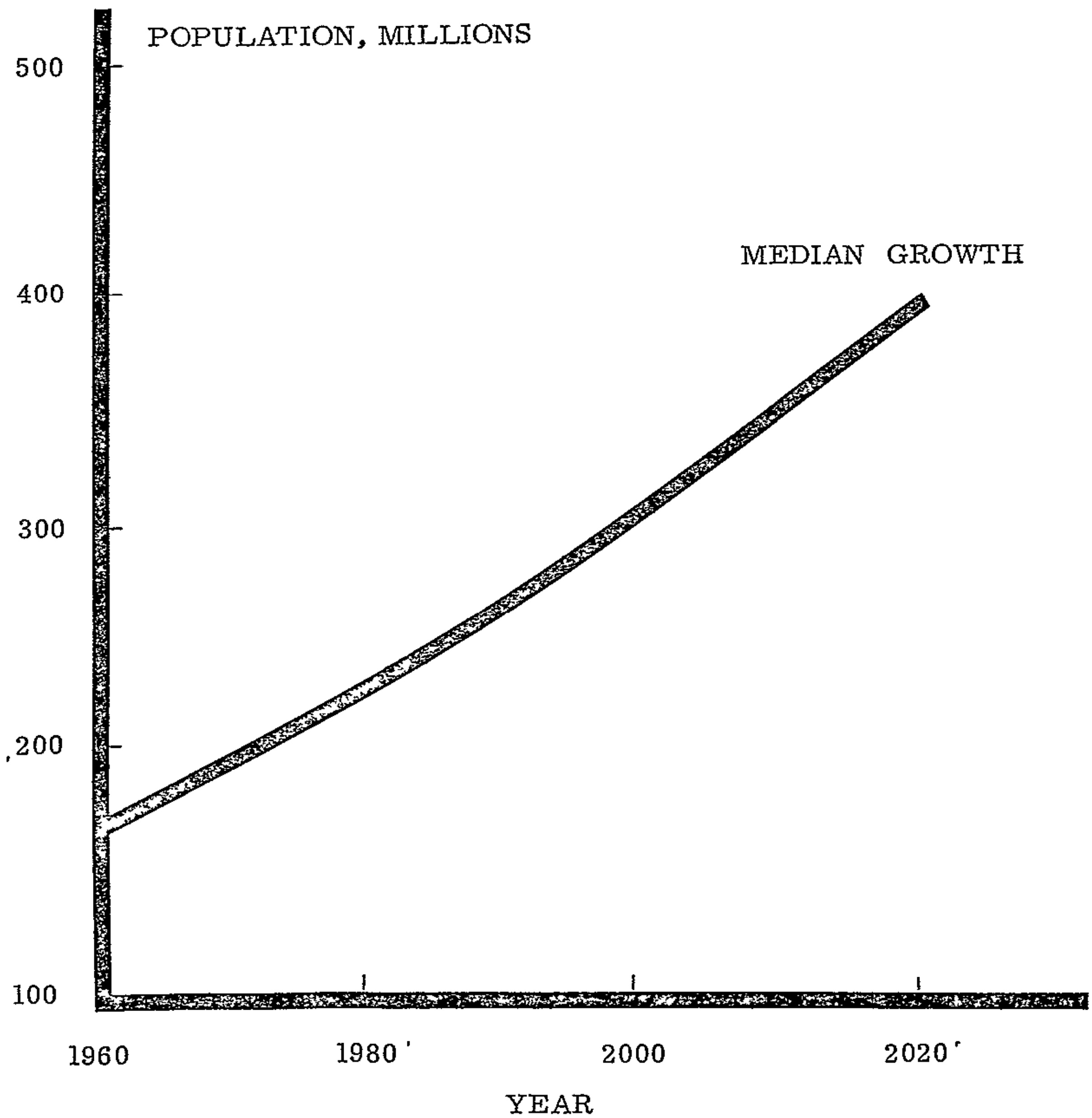
YEARLY U.S. EXPENDITURES FOR WATER RESOURCE

FEDERAL PROGRAMS
STORAGE COLLECTION & RECIRCULATION

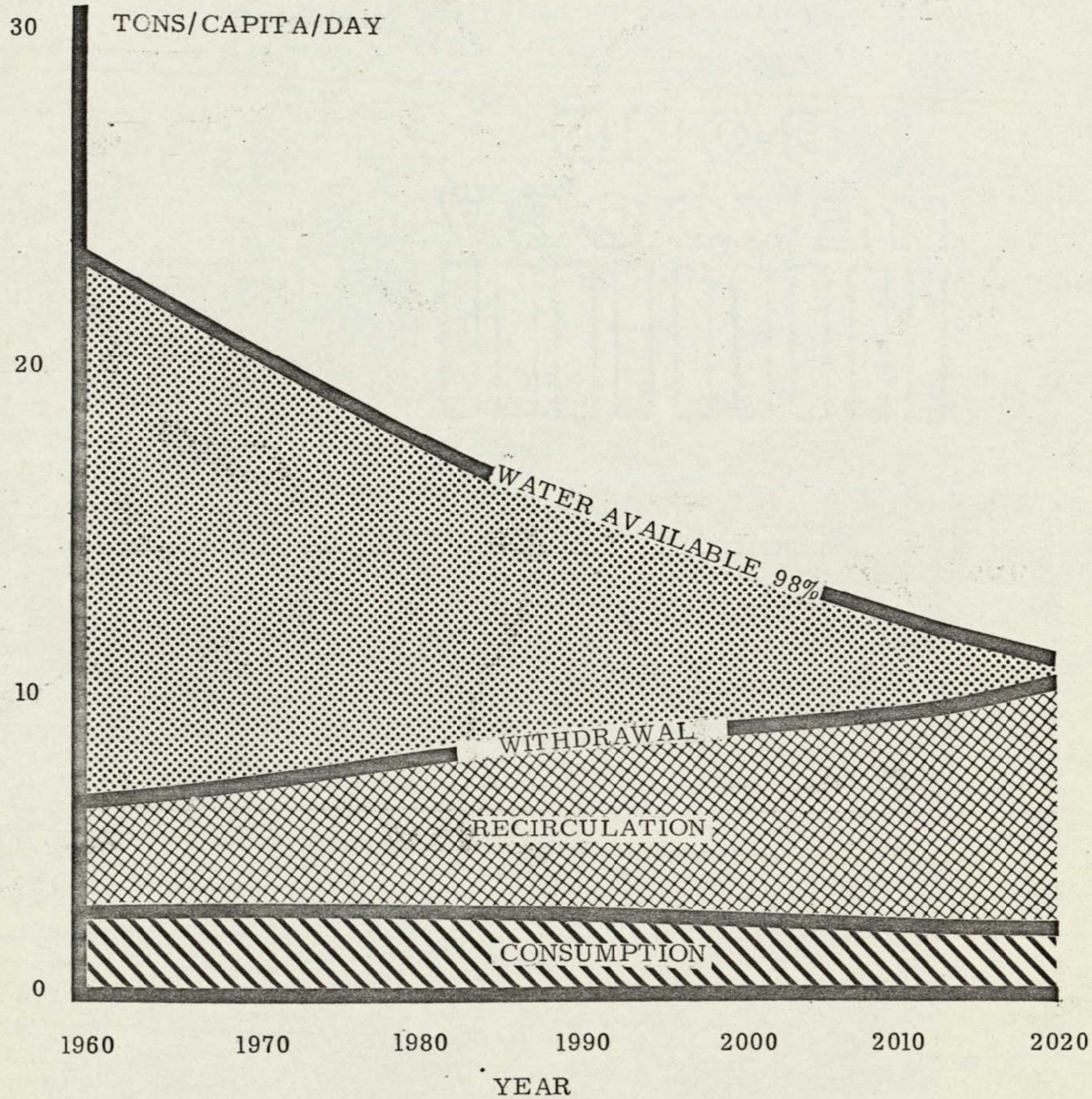


Even at a median rate of population and per capita demand growth, the fresh water supply per capita will just equal the demand within the next 50 years. This assumes no major technological innovations.

U.S. POPULATION PROJECTION

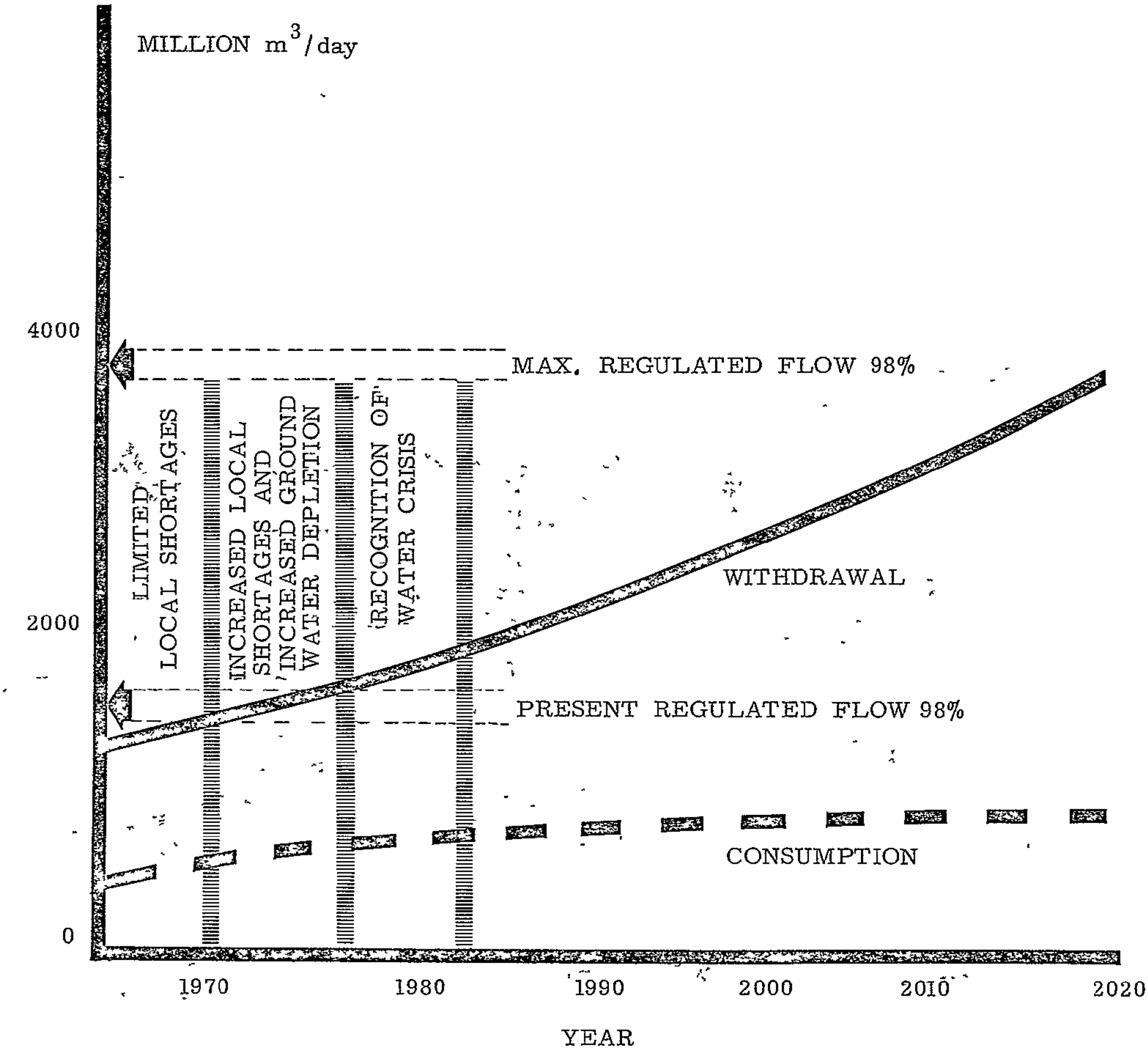


U.S. WATER SUPPLY AND WATER USE

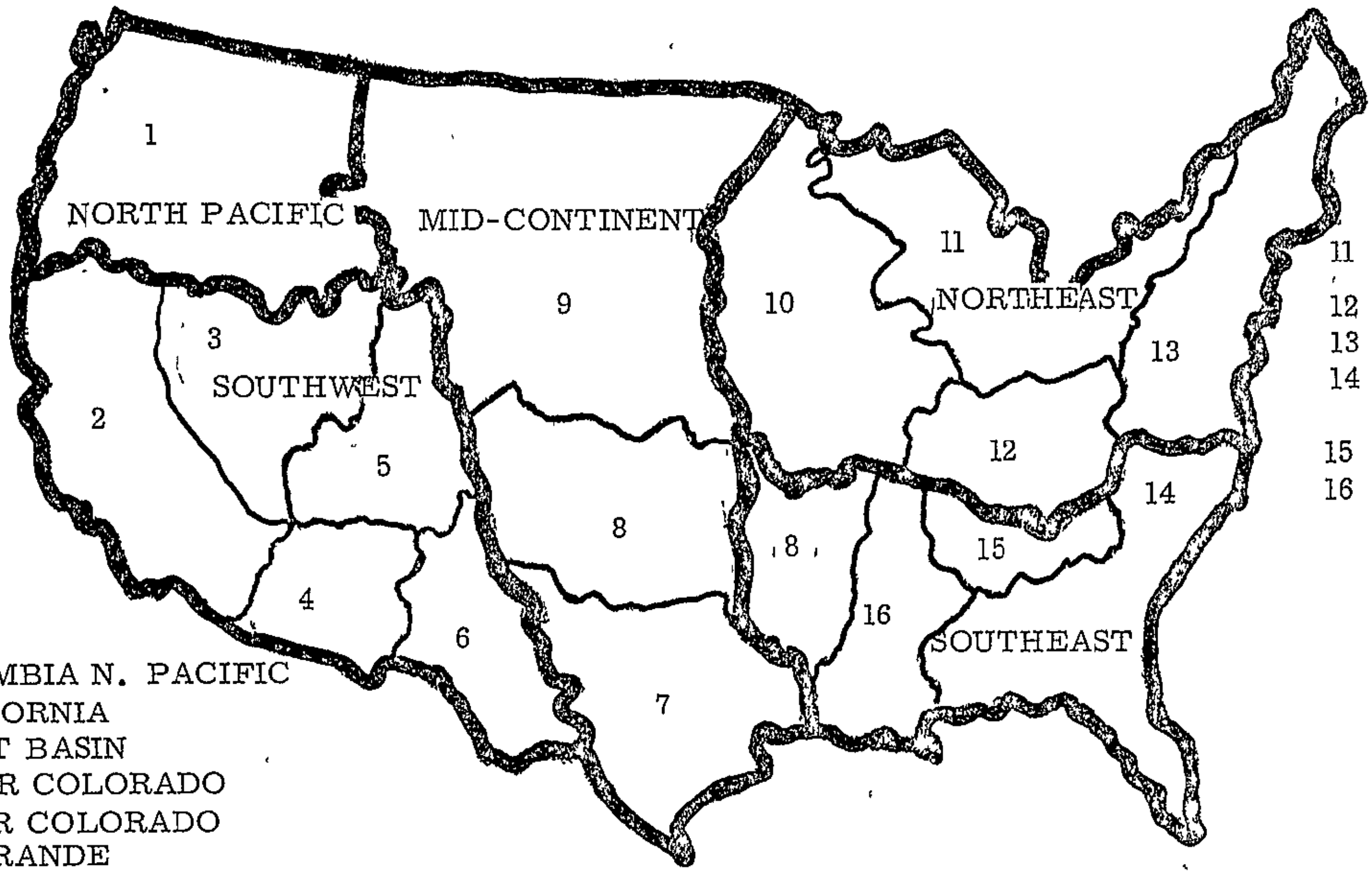


The continued reliance upon current technology of waterworks, in the absense of major technological innovation, portends an impending era of water scarcity.

THE APPROACHING U.S. WATER PROBLEM



The criticality of the water supply-demand gap varies with the region.



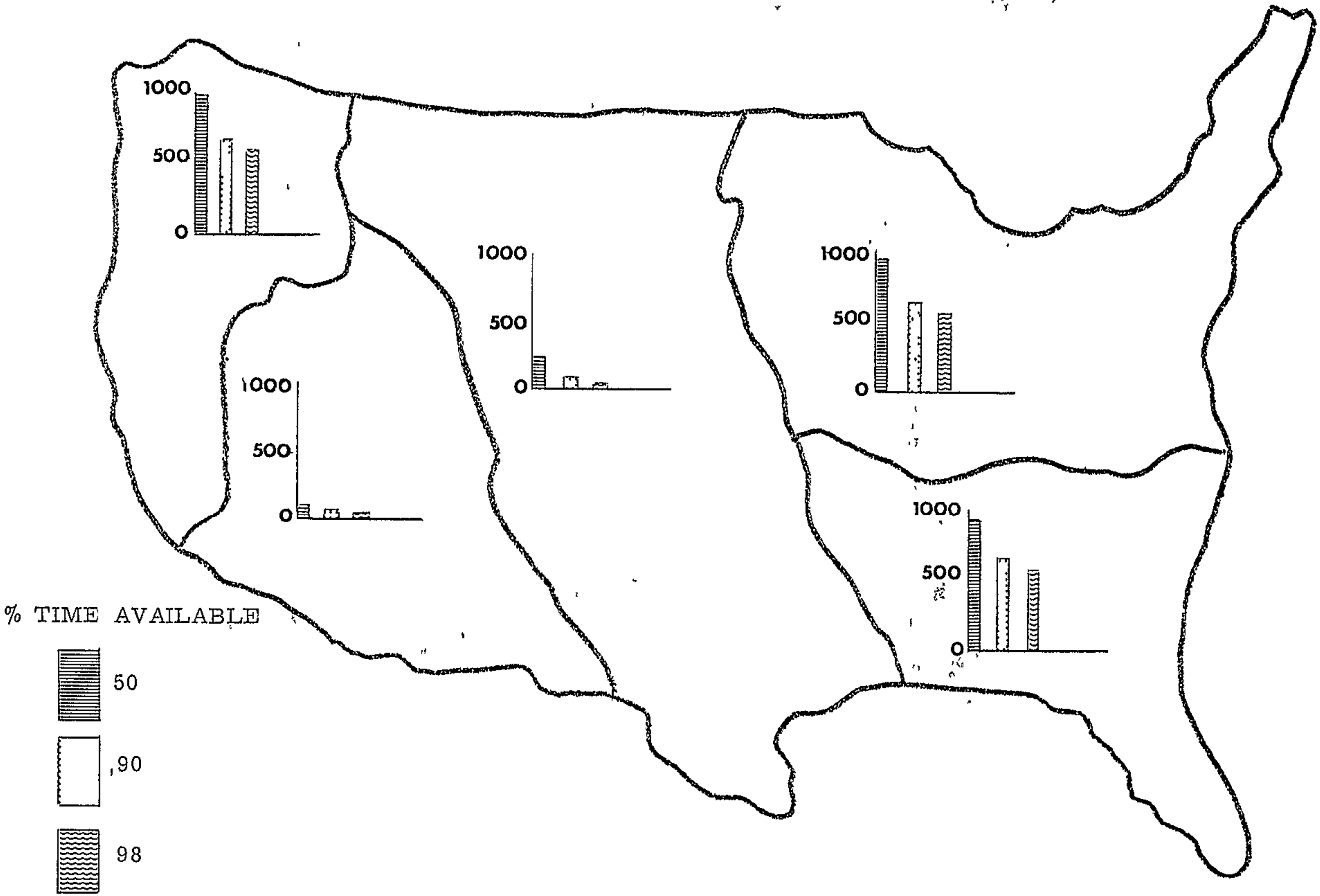
1 COLUMBIA N. PACIFIC
2 CALIFORNIA
3 GREAT BASIN
4 LOWER COLORADO
5 UPPER COLORADO
6 RIO GRANDE
7 TEXAS-GULF
8 ARKANSAS W. R.
9 SOURIS-RED-RAINY MISSOURI
10 UPPER MISSISSIPPI

11 GREAT LAKES
12 OHIO
13 NORTH ATLANTIC
14 SOUTH ATLANTIC GULF
15 TENNESSEE
16 LOWER MISSISSIPPI

WATER RESOURCE REGIONS

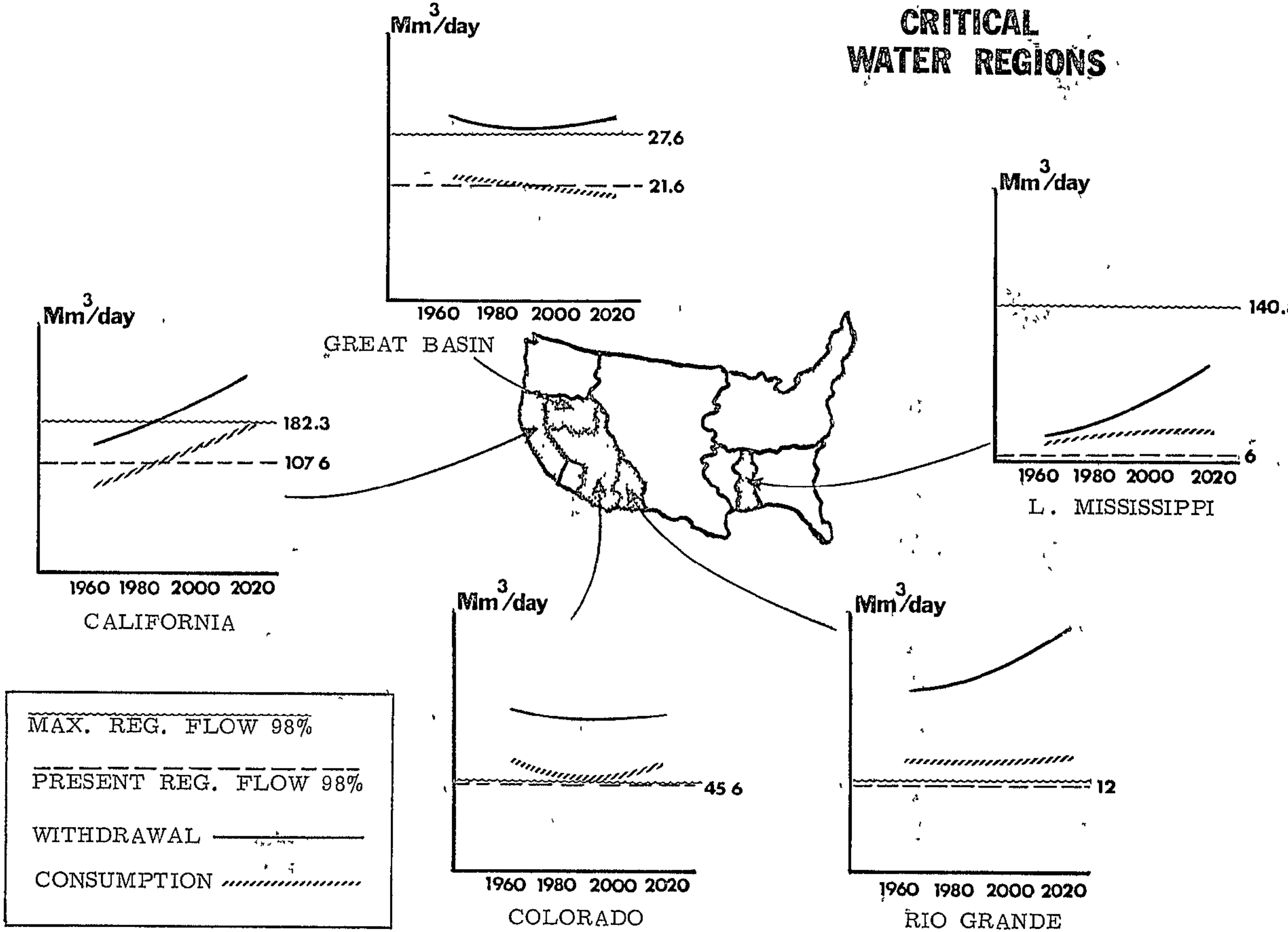
In part, it is due to the strong regional variations in water supply, indicated by the unit runoff (volume of runoff per unit time per unit area).

UNIT RUNOFF BY REGION = (m^3/DAY/Km^2)

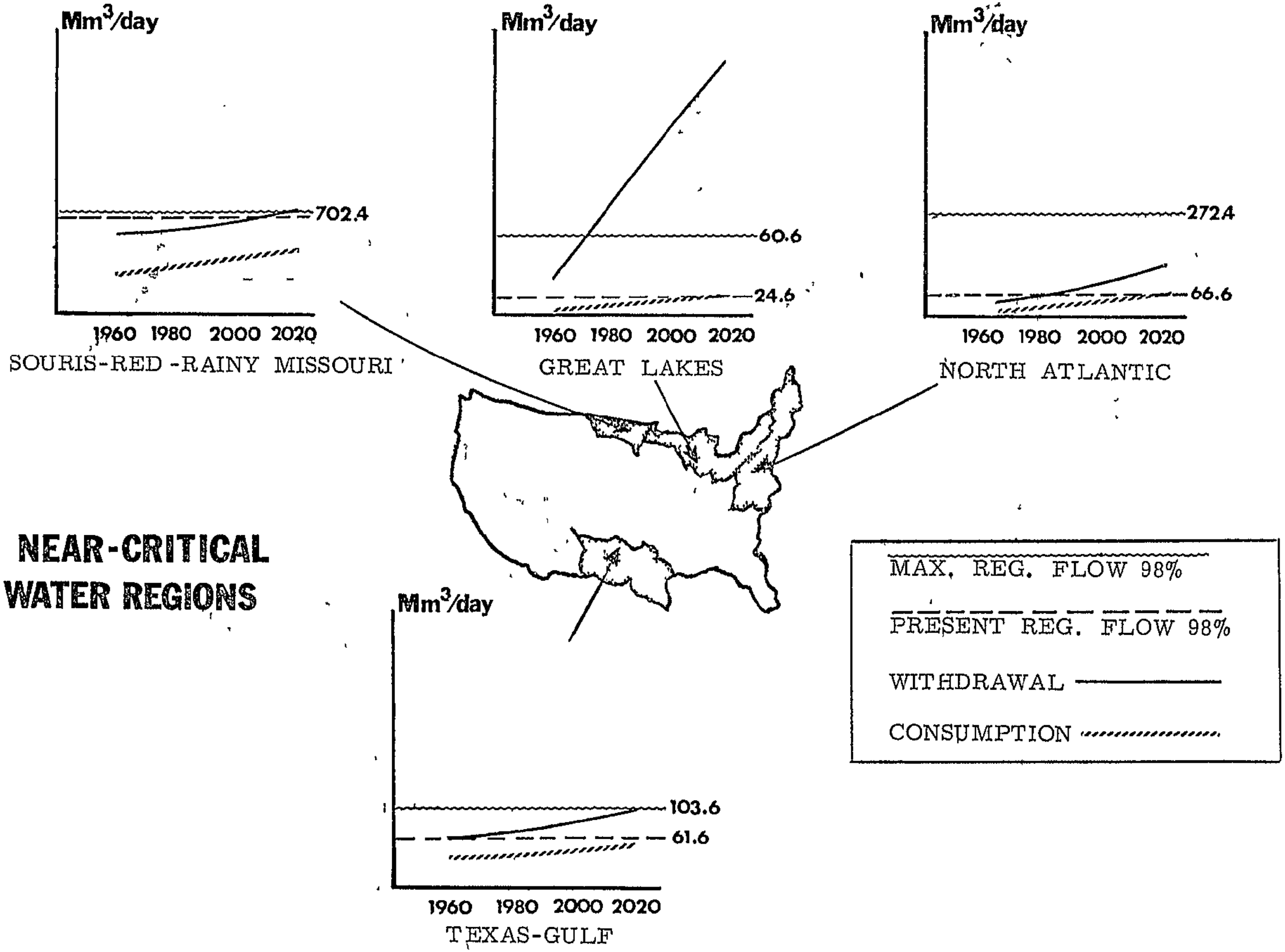


In part, it is due to the significant local variations in demand, .

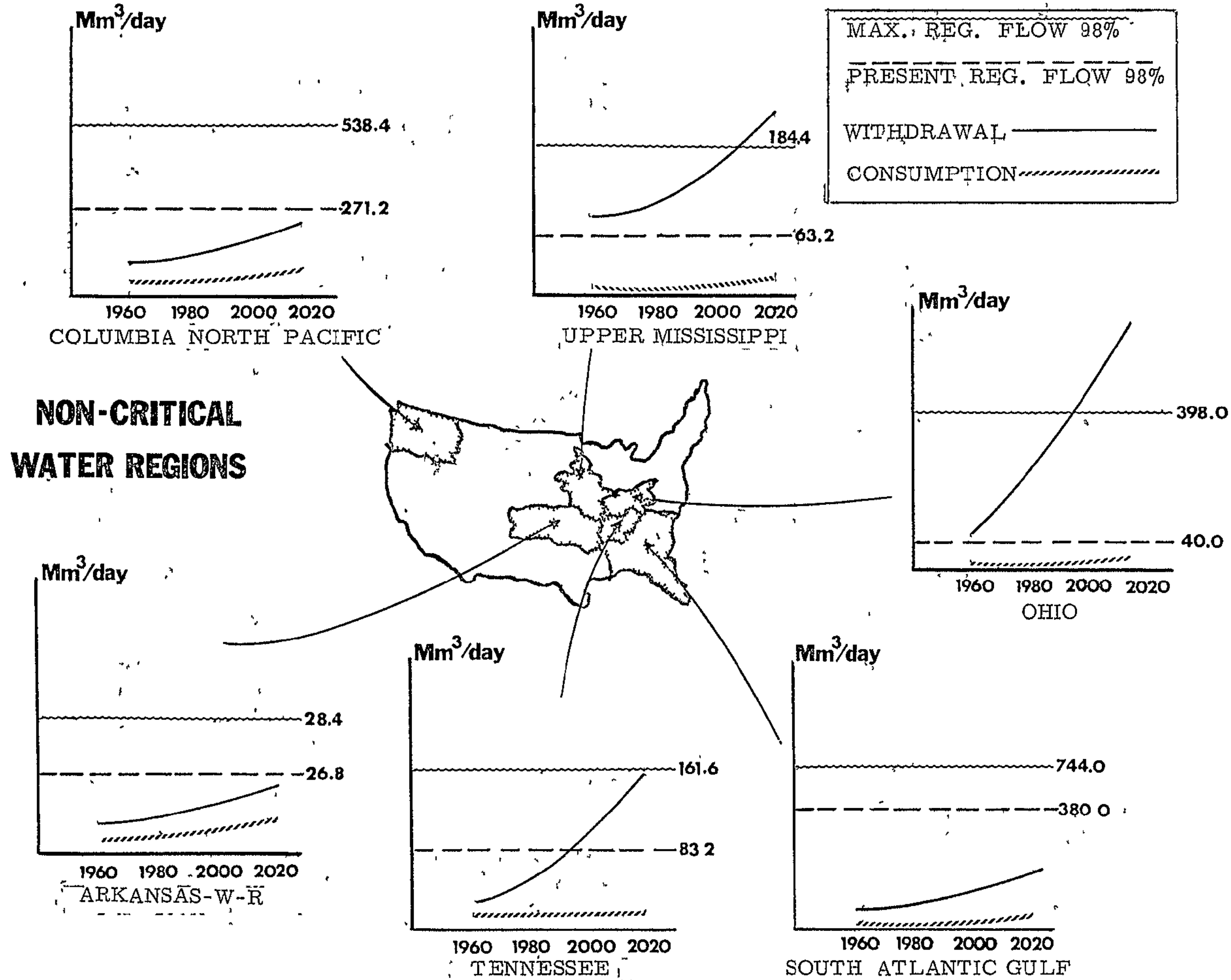
The currently critical regions.



CRITICAL
WATER REGIONS
Mm³/day
27.6
21.6
1960 1980 2000 2020
GREAT BASIN
Mm³/day
182.3
107 6
1960 1980 2000 2020
CALIFORNIA
Mm³/day
140.8
6
1960 1980 2000 2020
L. MISSISSIPPI
Mm³/day
45 6
1960 1980 2000 2020
COLORADO
Mm³/day
12
1960 1980 2000 2020
RIO GRANDE
MAX. REG. FLOW 98%
PRESENT REG. FLOW 98%
WITHDRAWAL
CONSUMPTION


NEAR-CRITICAL WATER REGIONS
Mm3/day
702.4
1960 1980 2000 2020
SOURIS-RED-RAINY MISSOURI
Mm3/day
60.6
24.6
1960 1980 2000 2020
GREAT LAKES
Mm3/day
272.4
66.6
1960 1980 2000 2020
NORTH ATLANTIC
Mm3/day
103.6
61.6
1960 1980 2000 2020
TEXAS-GULF
MAX. REG. FLOW 98%
PRESENT REG. FLOW 98%
WITHDRAWAL
CONSUMPTION

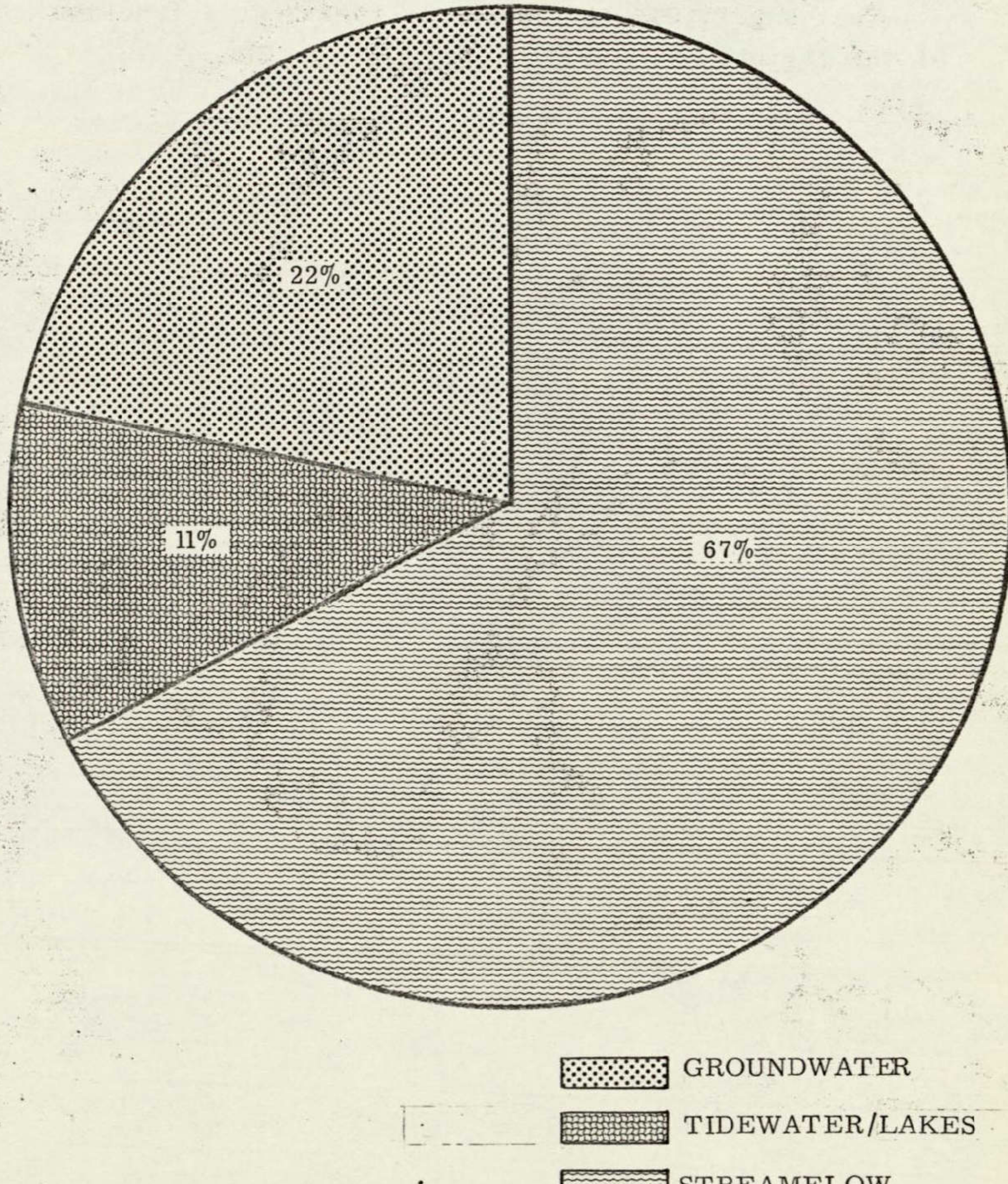
NON-CRITICAL WATER REGIONS



Not all U.S. water requirements are satisfied from the freshwater supplied by precipitation. Some requirements, notably cooling, are satisfied from sources of coastal and inland sea water.

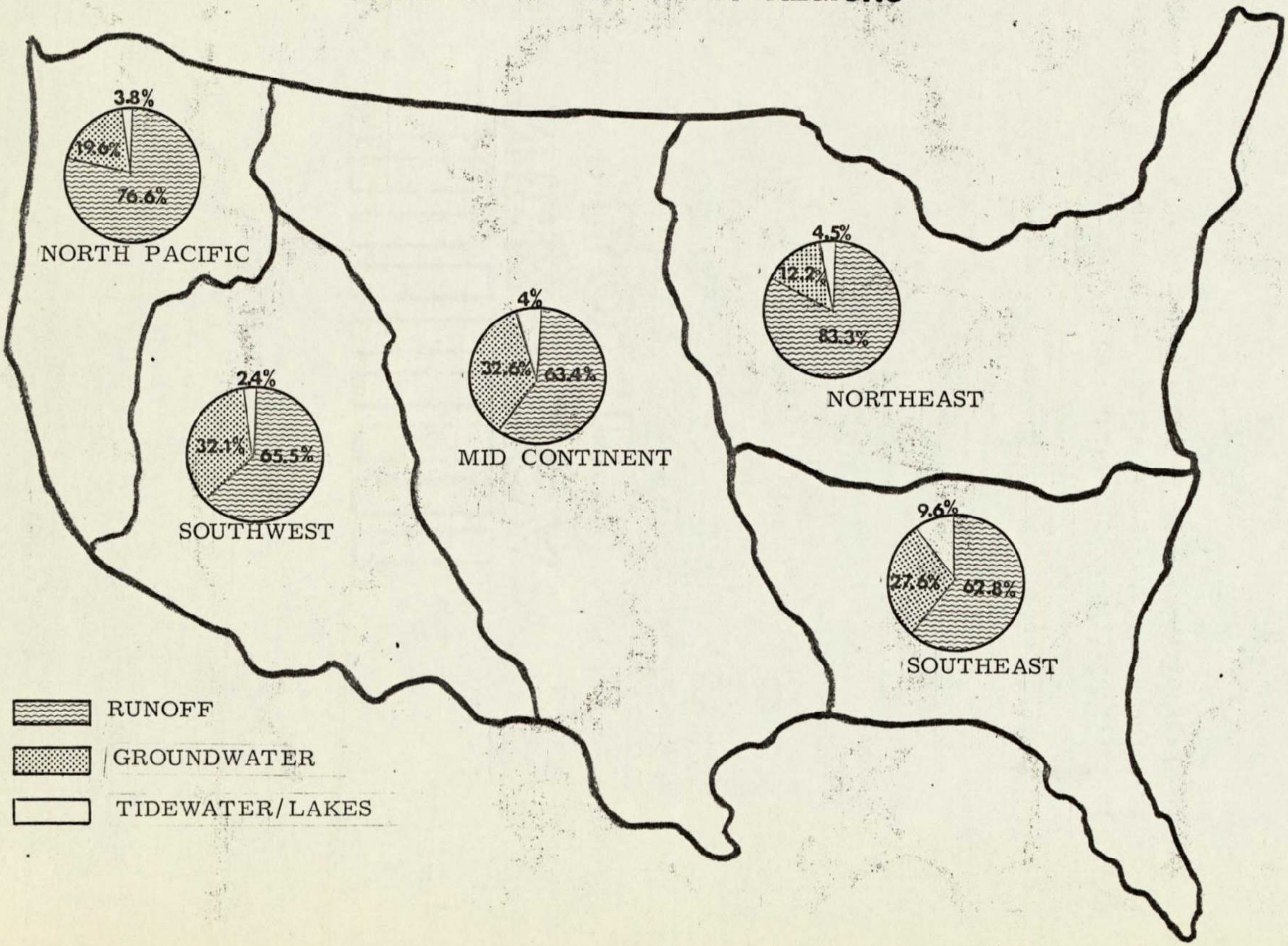
A significant portion of the U.S. water needs is supplied by groundwater. This supply, however, depends directly upon precipitation; it becomes depleted unless recharged from rainwater. Proper balance between recharge and withdrawals must be maintained: long-term withdrawal of groundwater cannot exceed the precipitation input.

SOURCES OF THE U.S. WATER SUPPLY



The composition of the supply varies as a function of the region.

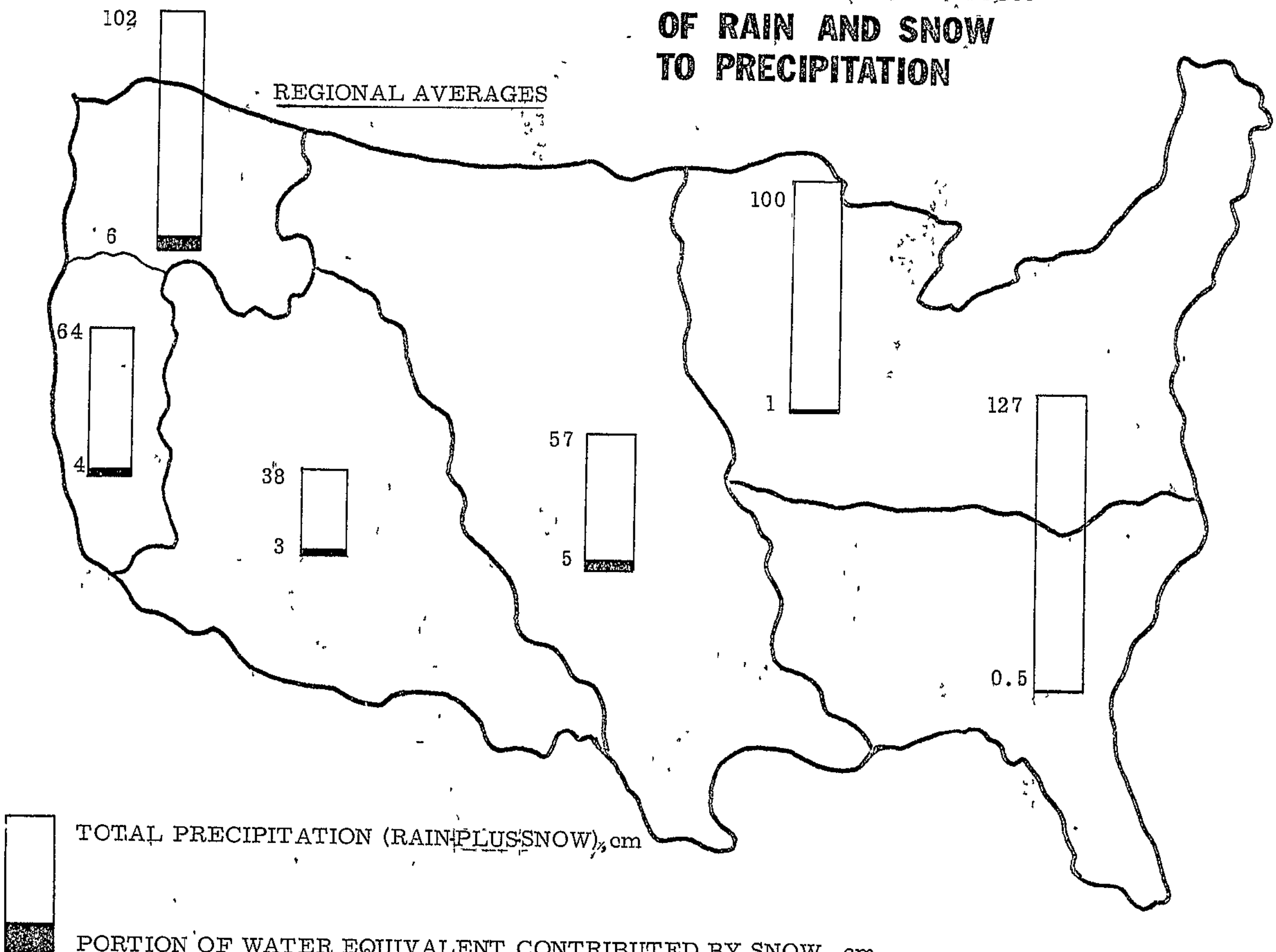
SOURCES OF WATER BY REGIONS



Part of the runoff is contributed by snow. Averaged over the U.S., snow might appear to contribute a relatively small portion of the water supply.

Such a conclusion is, however, unwarranted.

RELATIVE CONTRIBUTION OF RAIN AND SNOW TO PRECIPITATION



When looked at in more detail, the conversion of precipitation to runoff is likely to be more efficient for snow than for rain. Snow is less subject to evaporation; melt-waters flow over frozen or semi-frozen soil, and are thus less susceptible to infiltration. Furthermore, snow tends to concentrate in specific areas; thus, water losses are less for snow than for rainwater.

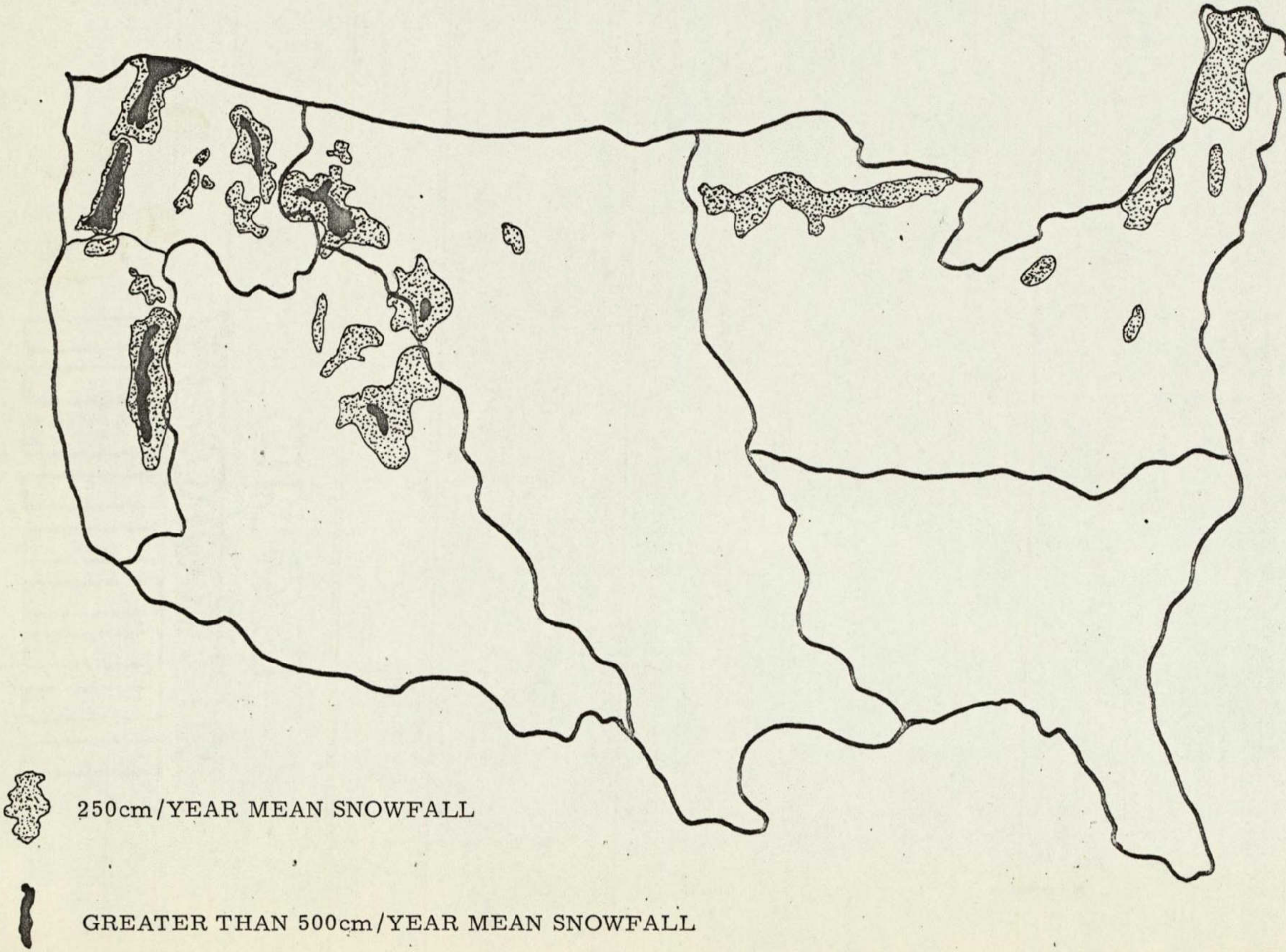
In the U.S., the large snow-supply areas are, perhaps by coincidence, located at the headwaters of water-critical regions. Thus snow, albeit a local phenomenon, is nonetheless locally important.

The actual contribution of snow to the U.S. water supply is poorly known, primarily because of the physical difficulty of mapping its extent and water equivalent. Its assessment is thus a significant challenge to satellite imagery.

Important investigations are:

1. Mapping the areas where snow is of importance.
2. Derivation of snowmelt models for the local areas where snow is a significant contributor to runoff.

HIGH SNOW PRECIPITATION AREAS



A fundamental concept in water resources planning and management is that of "regulated flow". Let us see its significance.

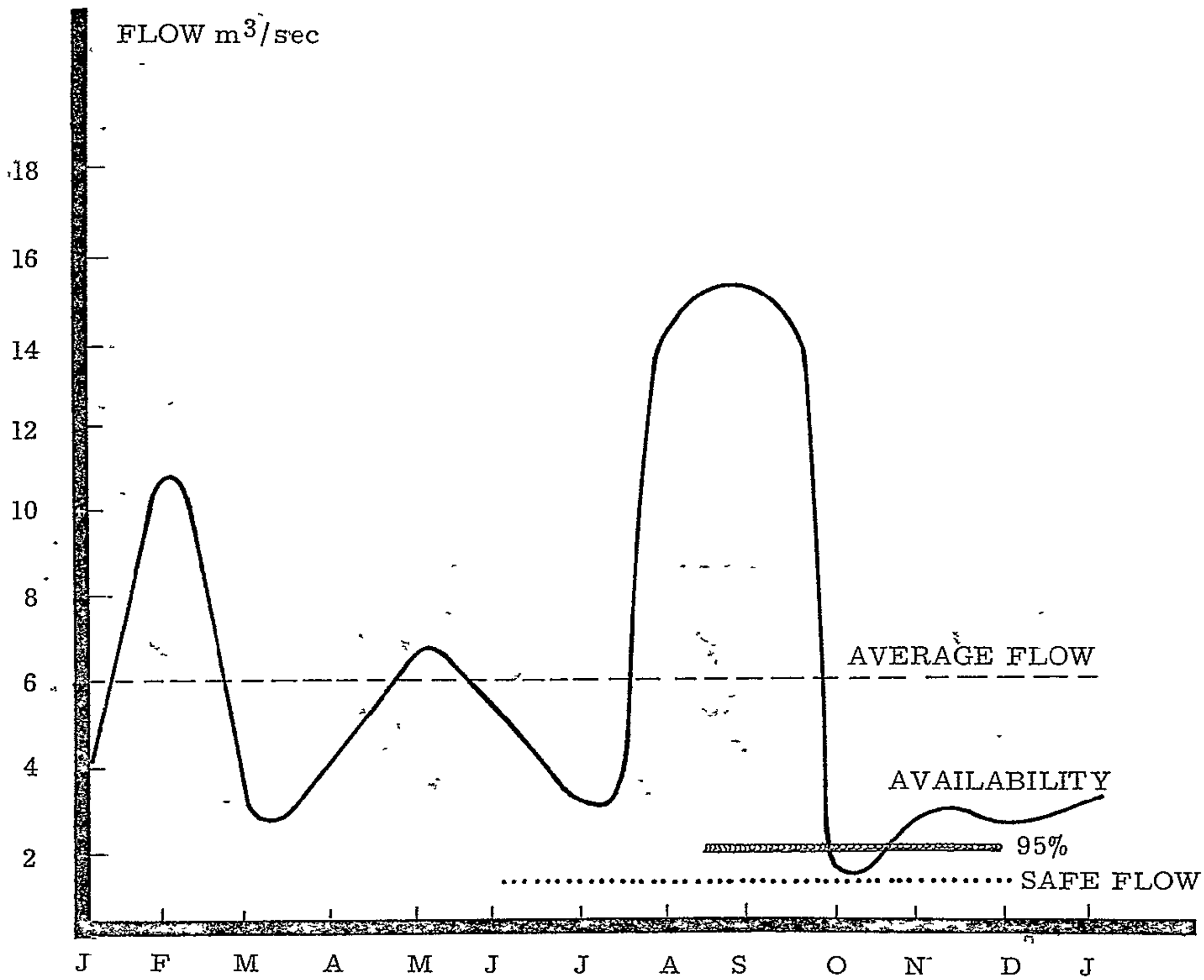
A typical river runoff pattern, in any one year, exhibits variations of flow. In the absence of regulatory works, the "safe yield" of the river, namely the flow which can be counted upon with certainty, is the lowest occurring flow. This safe yield then, in the absence of regulation, is the maximum "safe" demand which the river can supply.

If the water users can tolerate a specified time lapse over which the flow supply is less than the demand, or in other words, a maximum period of water scarcity, the demand can be higher than the safe demand. The 95% availability line, for example, defines a demand which is satisfied 95% of the time over the year. In the case illustrated, there will occur a "5% of the time" period of water scarcity, lasting 18 consecutive days.

It is clear that, even allowing periods of relative water scarcity, the permissible demand is significantly lower than the total available supply, which is the average flow.

In the typical case shown, the efficiency of utilization of the river's runoff, expressed as the ratio "Usable supply with 95% availability/average supply", is approximately 23%.

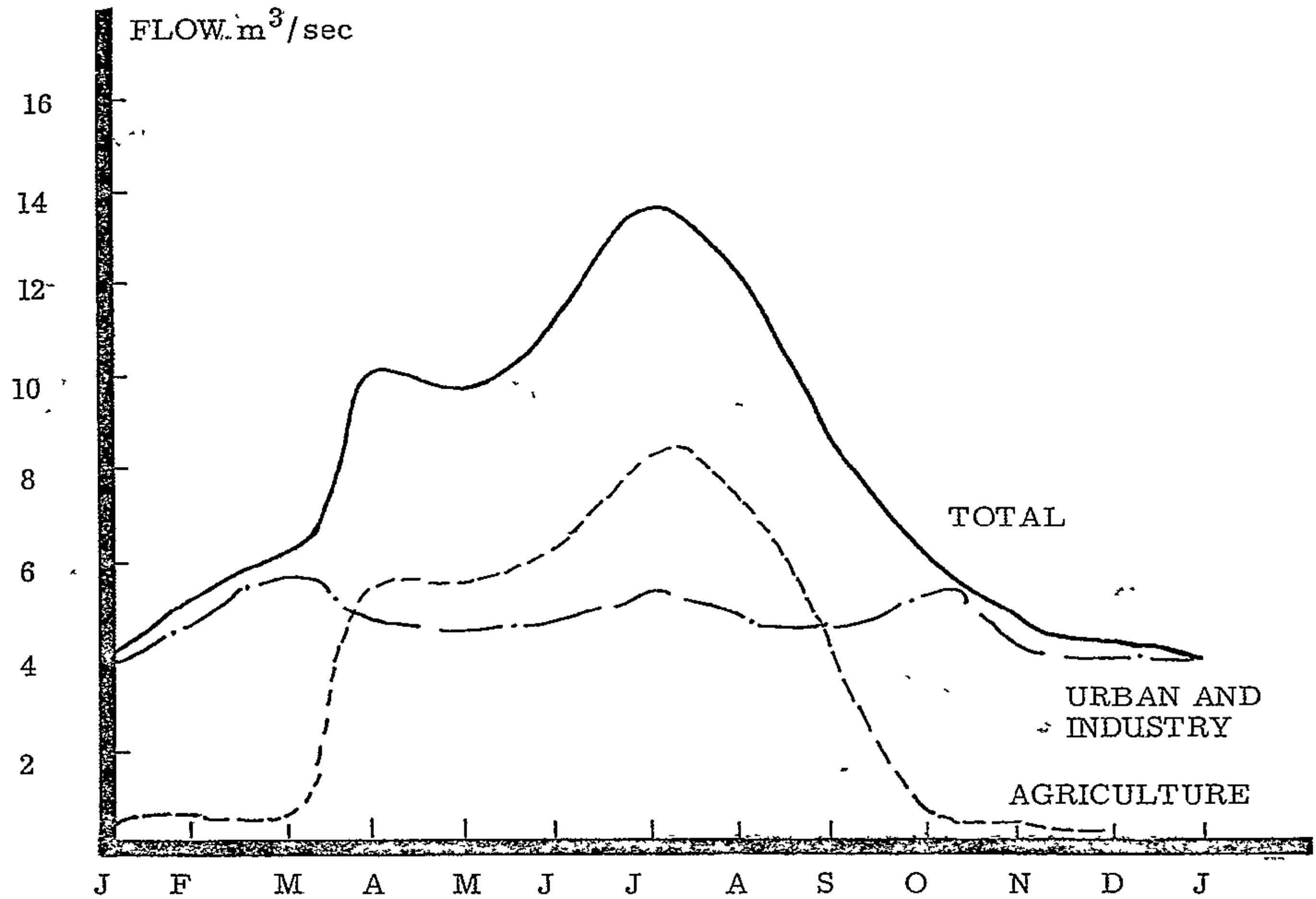
RIVER FLOW PATTERN



In practice, the demand for water is not constant. The situation worsens if the period of low flow coincides with a period of peak demand.

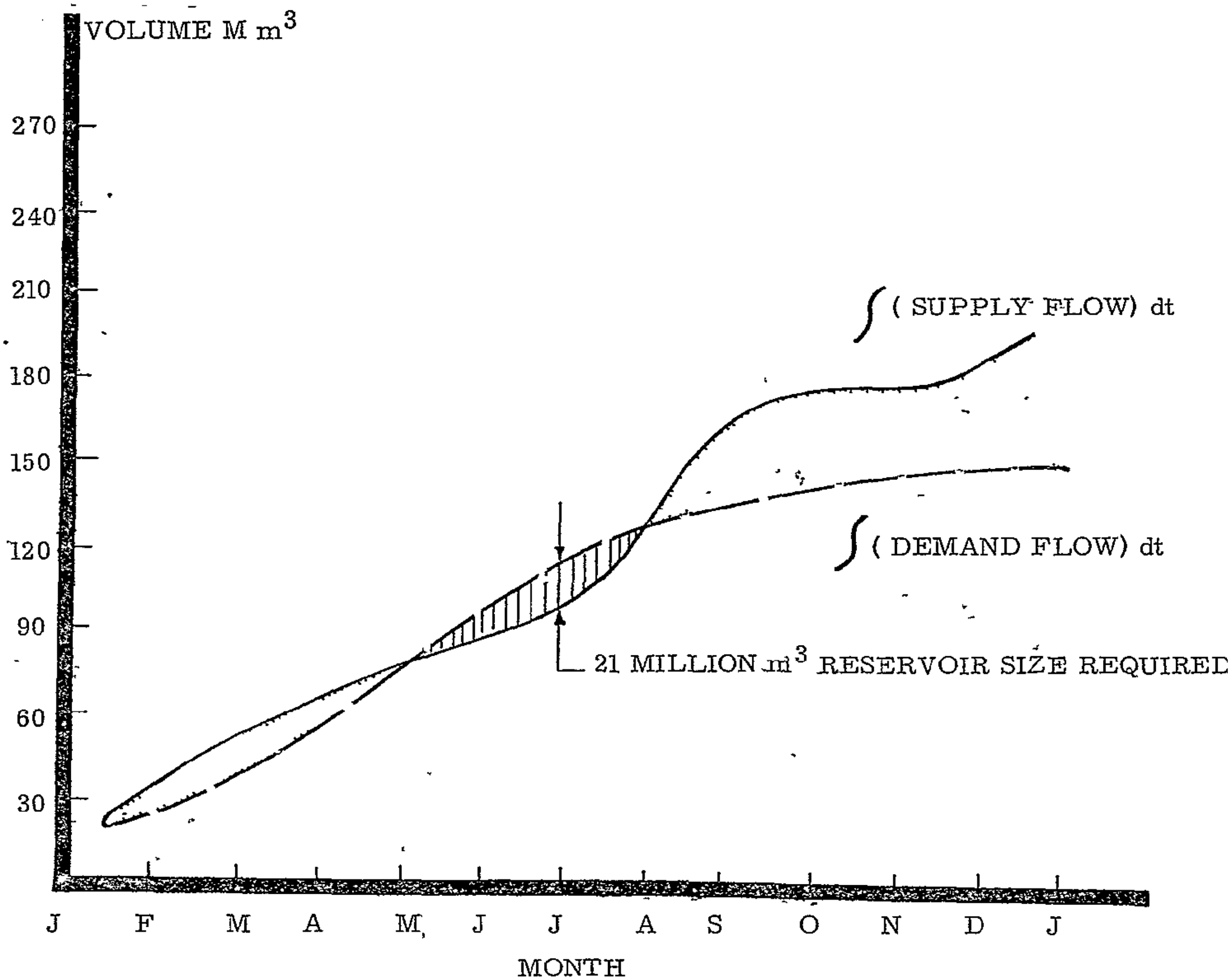
To increase the efficiency of the match between supply and demand, means are required to even out the variations in runoff river flow. These means are storage waterworks, which are most notably represented by reservoirs.

SEASONAL DEMAND OF WATER



The size of reservoir required can be determined in principle by computing the deficiency between the total water mass avilable, i.e., the integral of the flow-time curve, and the total mass demand, i.e., the integral of the demand-time curve.

PRINCIPLE OF RESERVOIR SIZING



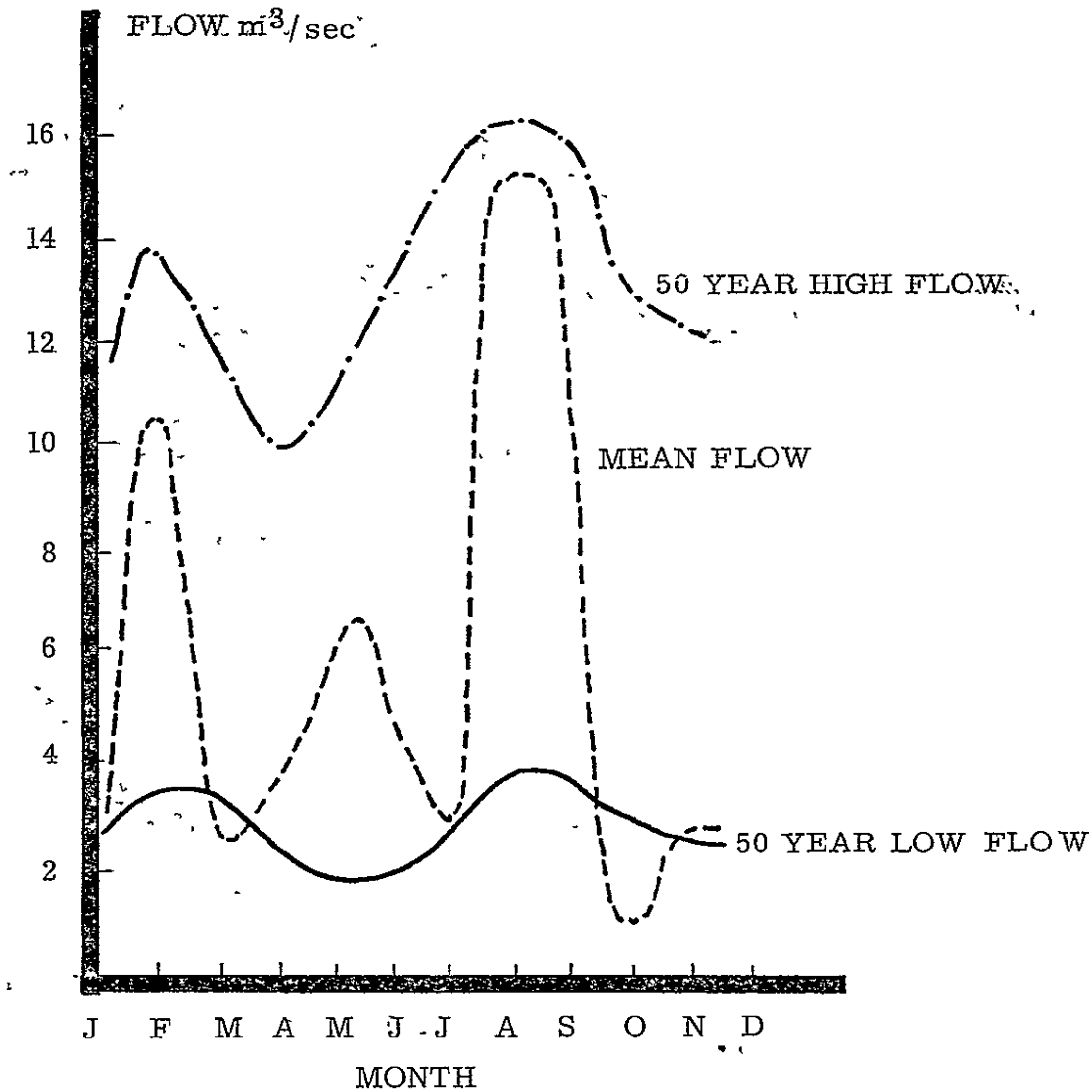
In nature, the river flow pattern does not repeat itself year after year. Real rivers exhibit significant yearly variations of flow, whose peak-to-trough ratio becomes larger the longer the time period under consideration.

Individual rivers, depending upon the region, can exhibit year-to-year fluctuations in average flow of as much as 10:1 over a 50-year period.

In the case of torrents, the fluctuation's peak-to-trough ratio reaches infinity.

In a sense, the instantaneous flow of rivers displays a behavior not unlike that of random noise, although with different statistics.

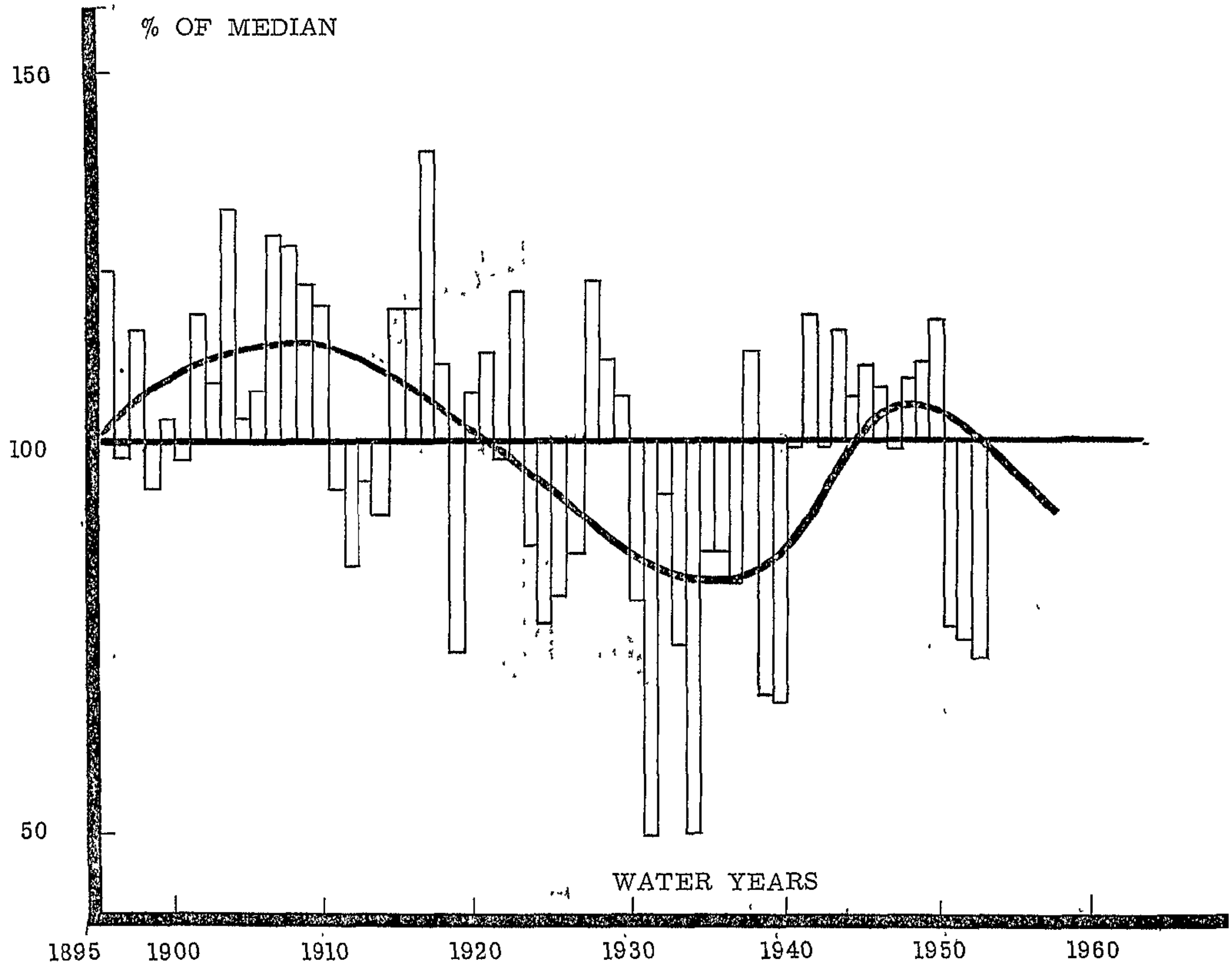
VARIABILITY OF RIVER FLOW



Even over an area as large as the continental U.S., the average runoff exhibits variations of order 3:1 over a 60-year period.

These fluctuations mandate that the sizing of reservoirs be performed on statistical bases, rather than by the simplified procedure previously shown.

LONG TERM TREND IN STREAMFLOW IN THE U.S.

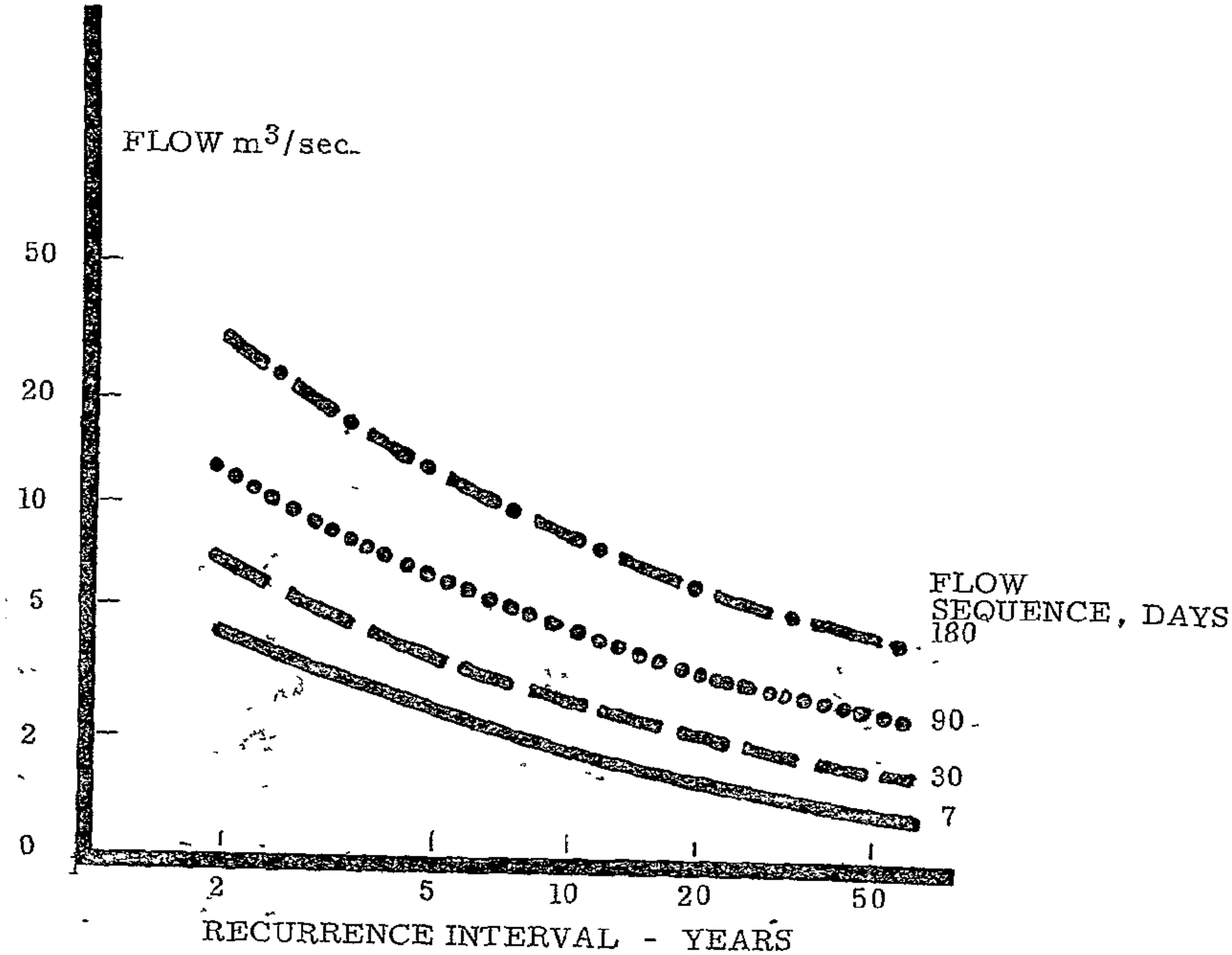


The statistical information can take various forms, and be displayed in diverse fashion. It boils down eventually to the description, for each river, of the statistics of the minimum and maximum available flow.

Minimum available flow means the flow which, over the period of years of record taken into consideration, is never less than a specified flow over a preassigned interval of consecutive days.

For example, a 98% reliable flow designates the event likely to occur on the average every 50 years. In the example illustrated, every 50 years there will occur one chance of the flow of the river being less than 0.6 m^3/sec for 7 consecutive days, or less than 4.8 m^3/sec for 180 consecutive days.

LOW FLOW STATISTICS

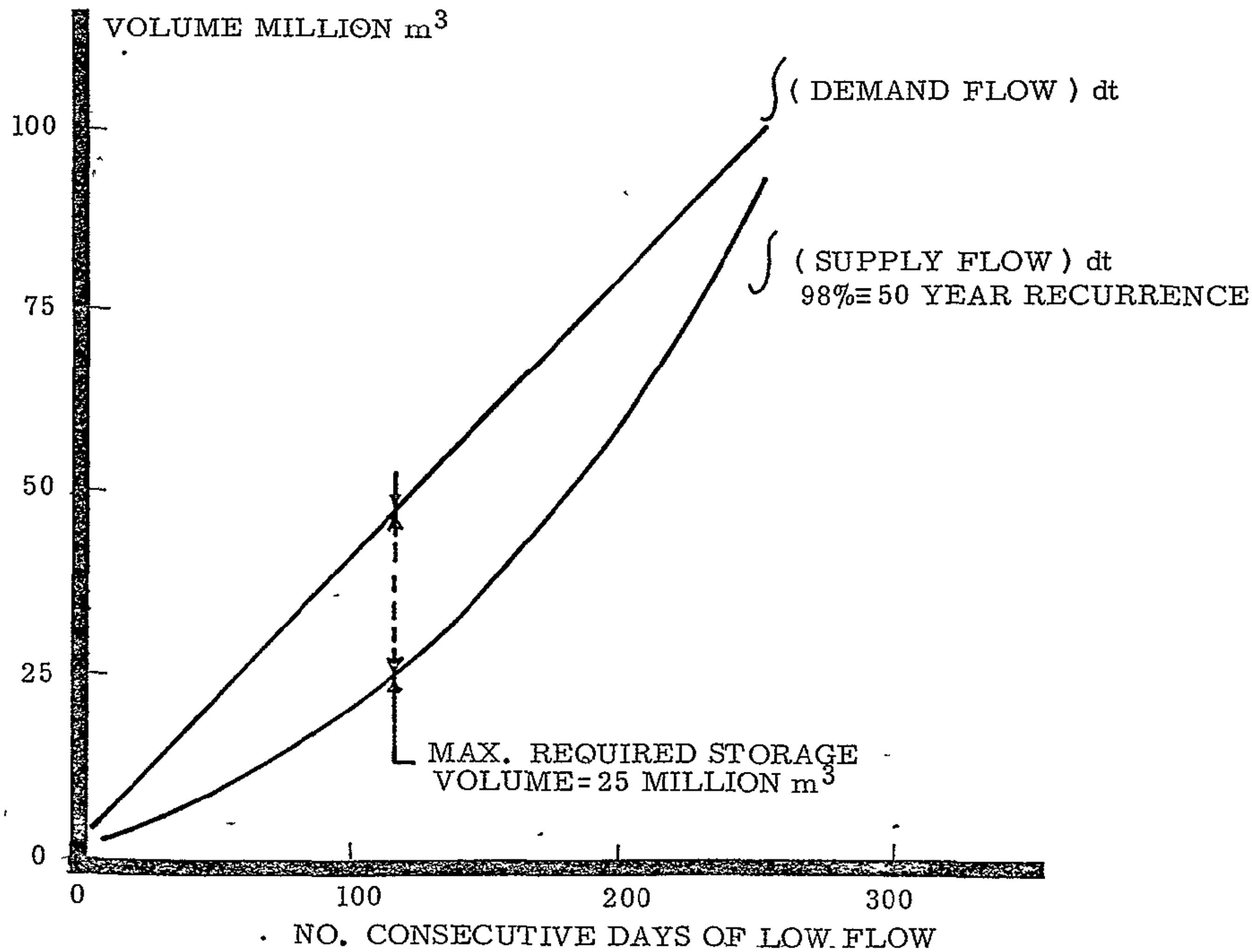


Statistical reservoir sizing is performed by comparing the water mass generated by the low-flow sequence against the demand. The maximum deficiency between demand and supply is the storage volume required to maintain the demand at its design level during periods of "worst" low flow.

The choice of the low-flow recurrence period depends upon design criteria; 50 years (98%) is typical for the larger projects.

The recent trend is to increase the design recurrence period towards the 100-year events.

STORAGE REQUIREMENT FOR RELIABLE SUPPLY

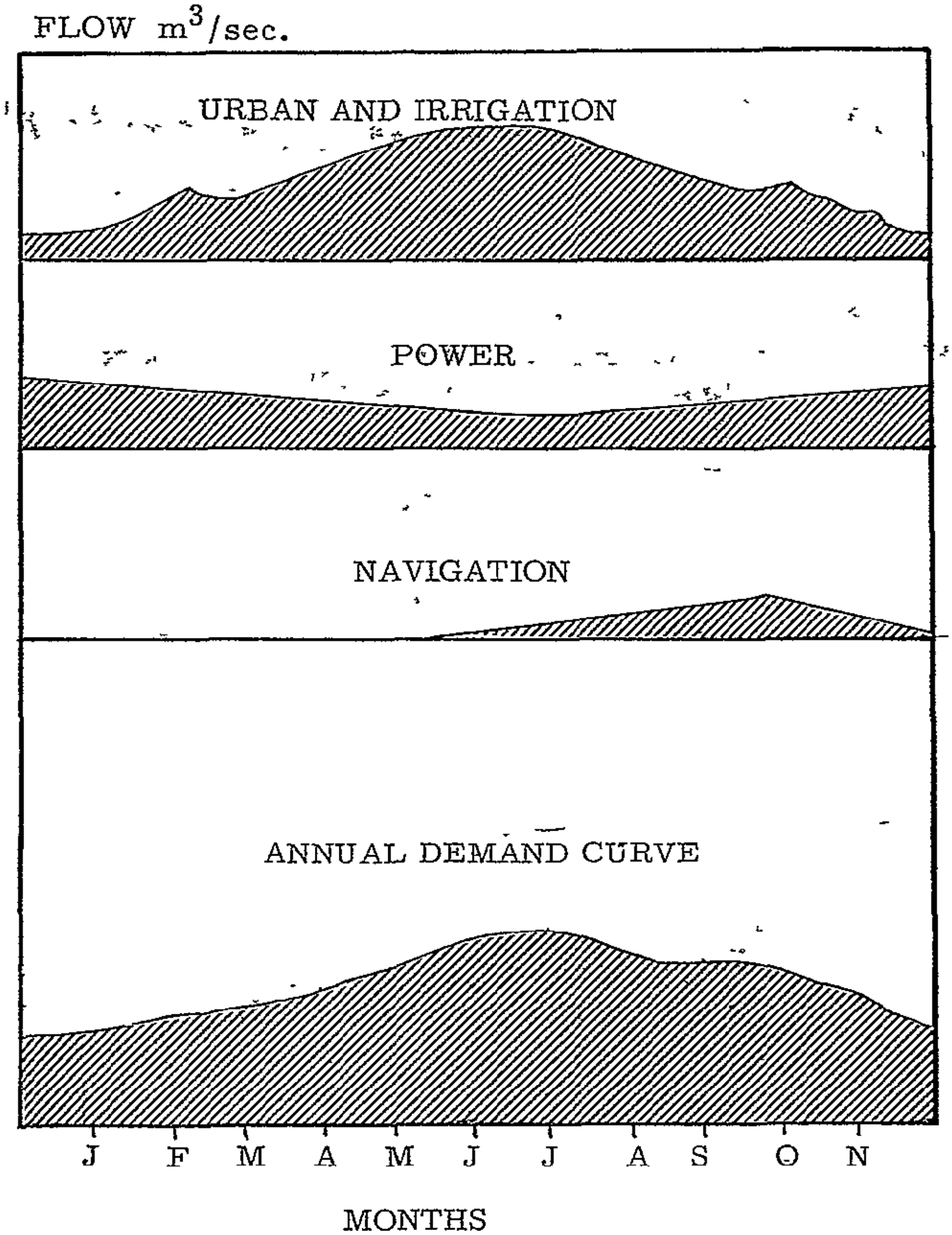


Modern trend in the design of U.S. reservoirs is to size them, not solely to provide water supply, but for multiple use; i.e., water supply plus either one or more of:

- Hydropower
- Industrial/Electric Cooling
- Recreation Uses
- Navigation
- Flood Protection

Multiple use gives rise to significantly expanded reservoir capacity requirements.

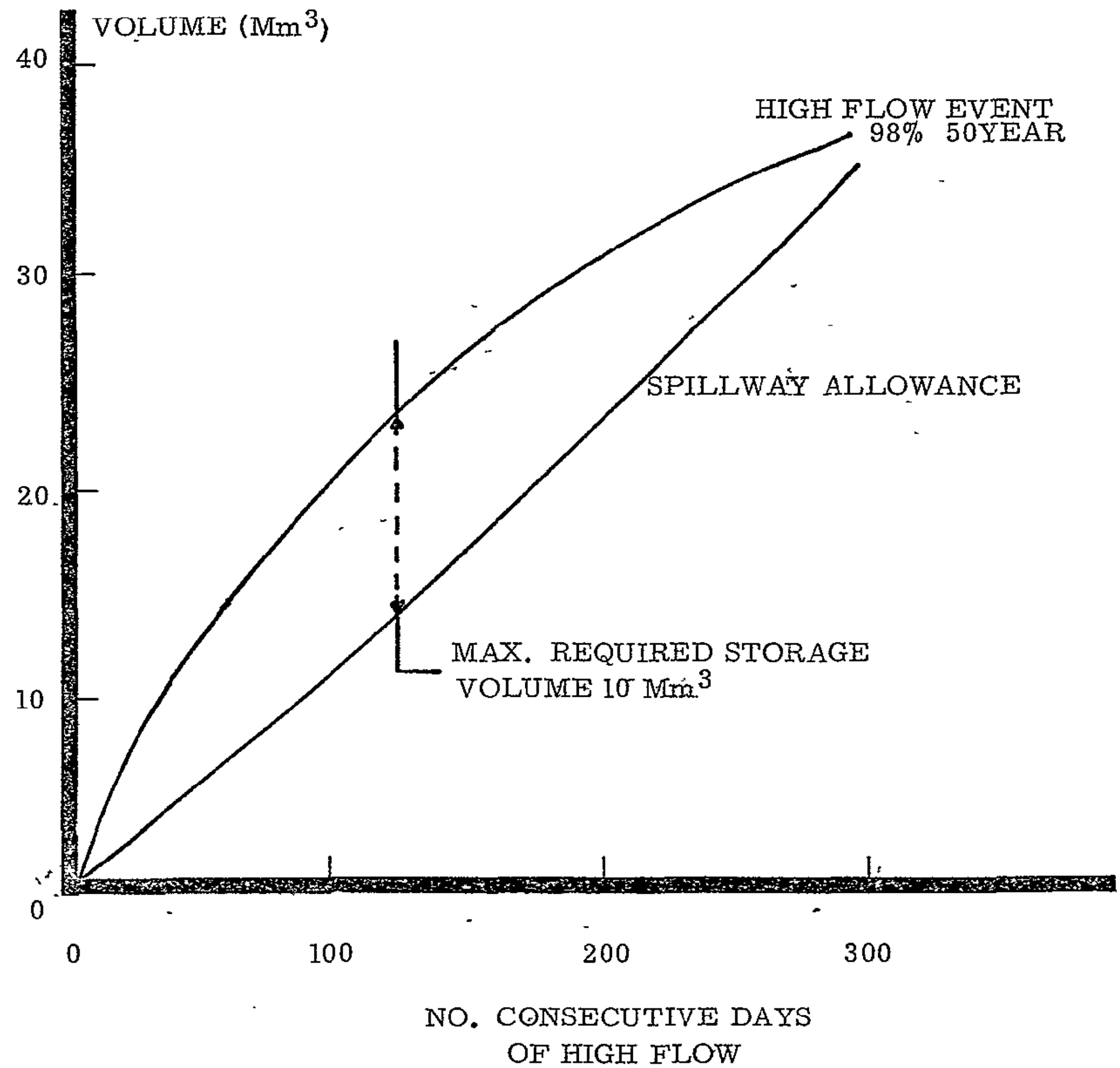
MULTIPLE DEMAND PATTERN



For example, if, in addition to supplying demand, the reservoir must protect against floods, the high flow sequence must be taken into account.

The procedure is similar to the one shown for low flow events. The demand curve is replaced by the spillway allowance, which is the maximum safe outflow from the reservoir. The maximum excess between high flow water mass and the spillway allowance is the storage volume required to accommodate the floodwaters.

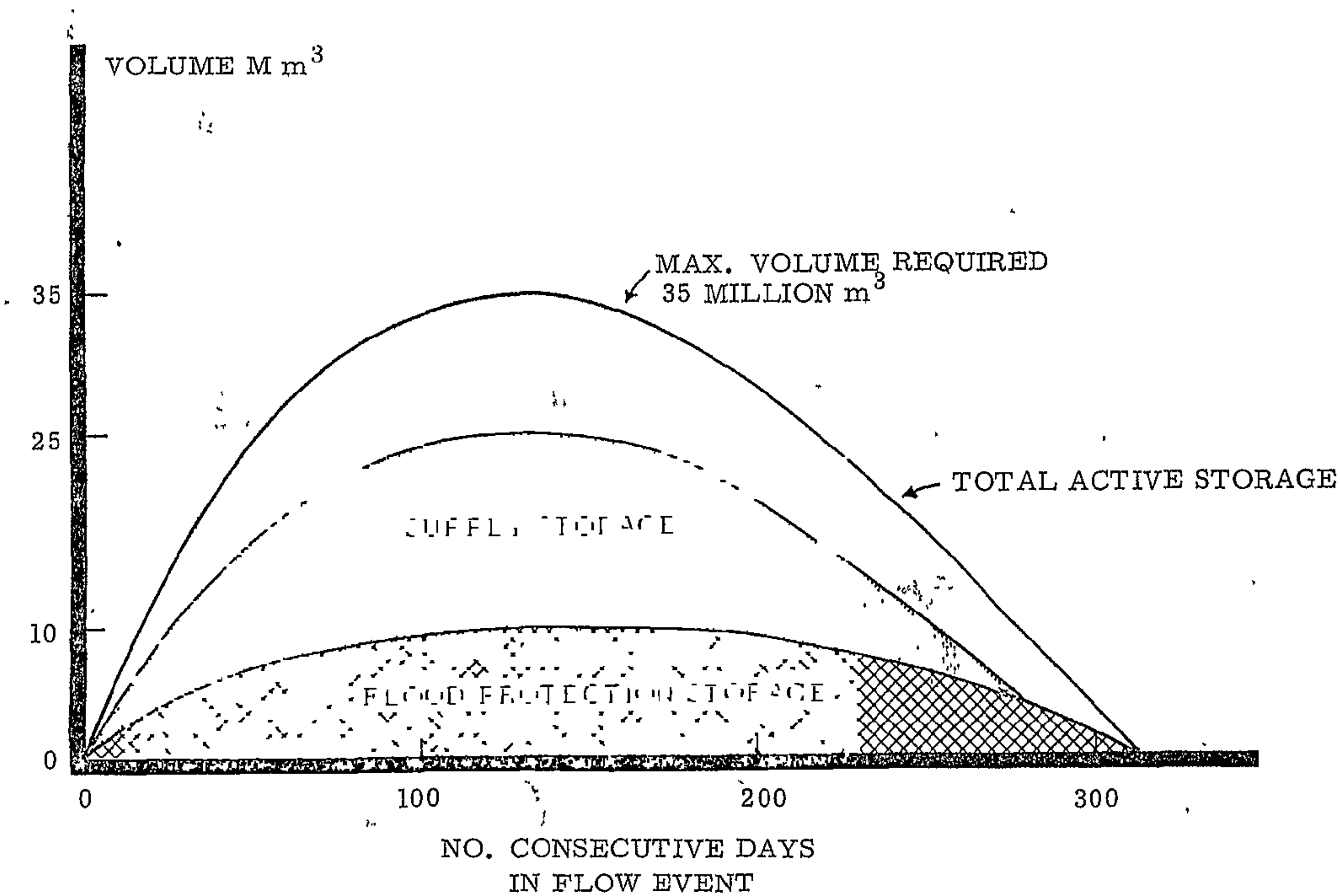
STORAGE REQUIREMENT FOR FLOOD PROTECTION



The sum of the storage required for supply/demand matching, and for flood protection is, under the assumptions made, the total active storage required.

The assumptions were: (a) choice of the same recurrence frequency (98% or fifty-years) for both supply and flood, and (b) constant demand.

REQUIRED ACTIVE RESERVOIR STORAGE



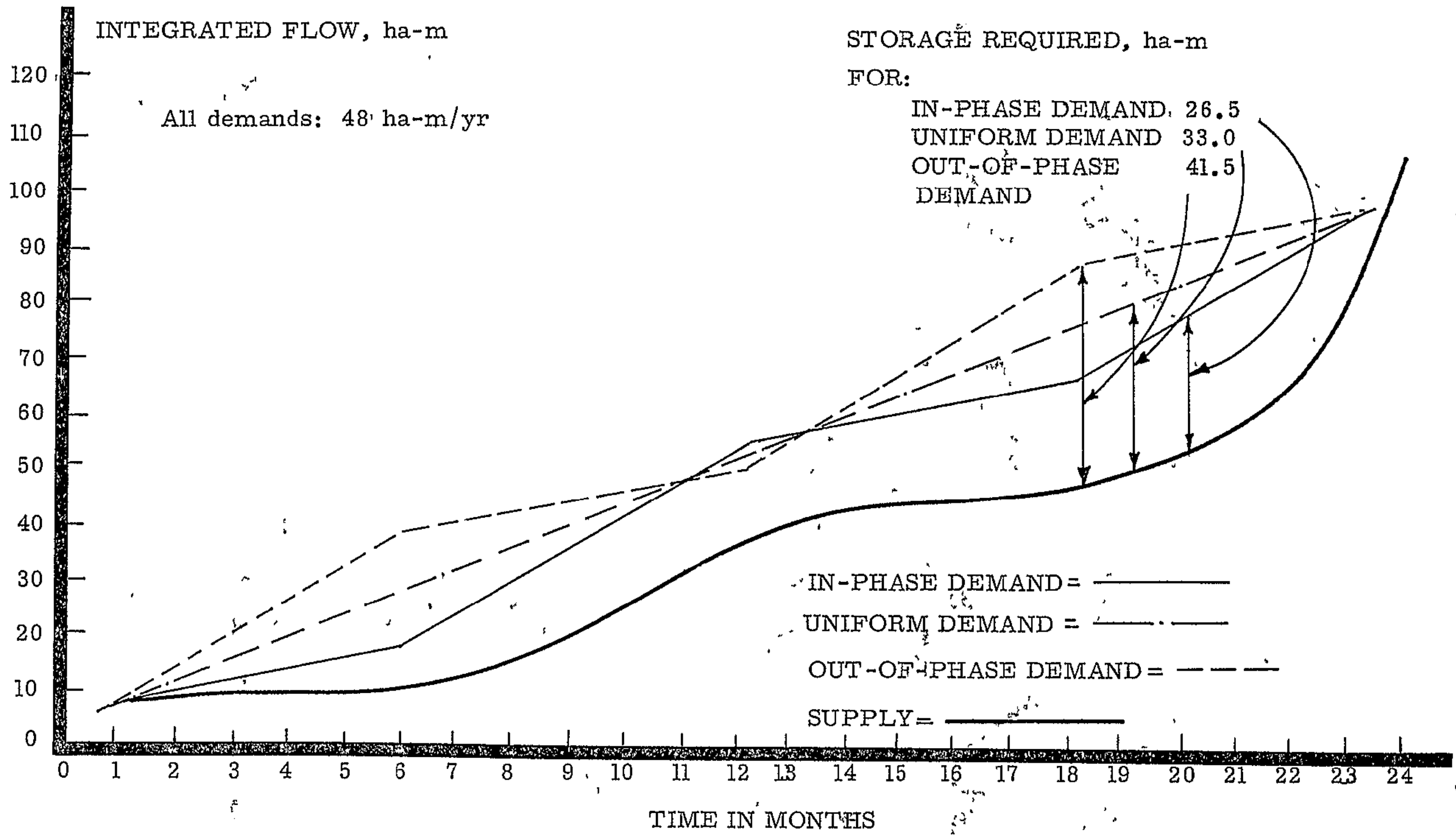
Departure from these assumptions, taking into account the realistic requirements of the water users, can lead to reservoir storage requirements more optimal than the simple sum of demand plus flood requirements, with consequent improvements in benefit/cost. This requires obtaining the statistics of the demand, which is yet a poorly explored area.

Particularly for agricultural irrigation demand, the application of remote sensing technology appears well suited to this data-gathering task. Important investigations are:

1. Mapping of the evapotranspiration potential.
2. Derivation of evapotranspiration models, capable of short-term (daily-weekly) response, and which can accept as input variables parameters measureable remotely (insolation, cloud cover).

This subject is further expanded, later in this volume, under the subsection "Irrigation".

EFFECT OF DEMAND SEQUENCE ON STORAGE REQUIREMENTS



The physical design of a reservoir must take into account, in addition to the storage required to meet single or multiple demand:

Excess storage required to compensate for evaporation.

Excess storage required to compensate for the build-up of sediments entrained by the river.

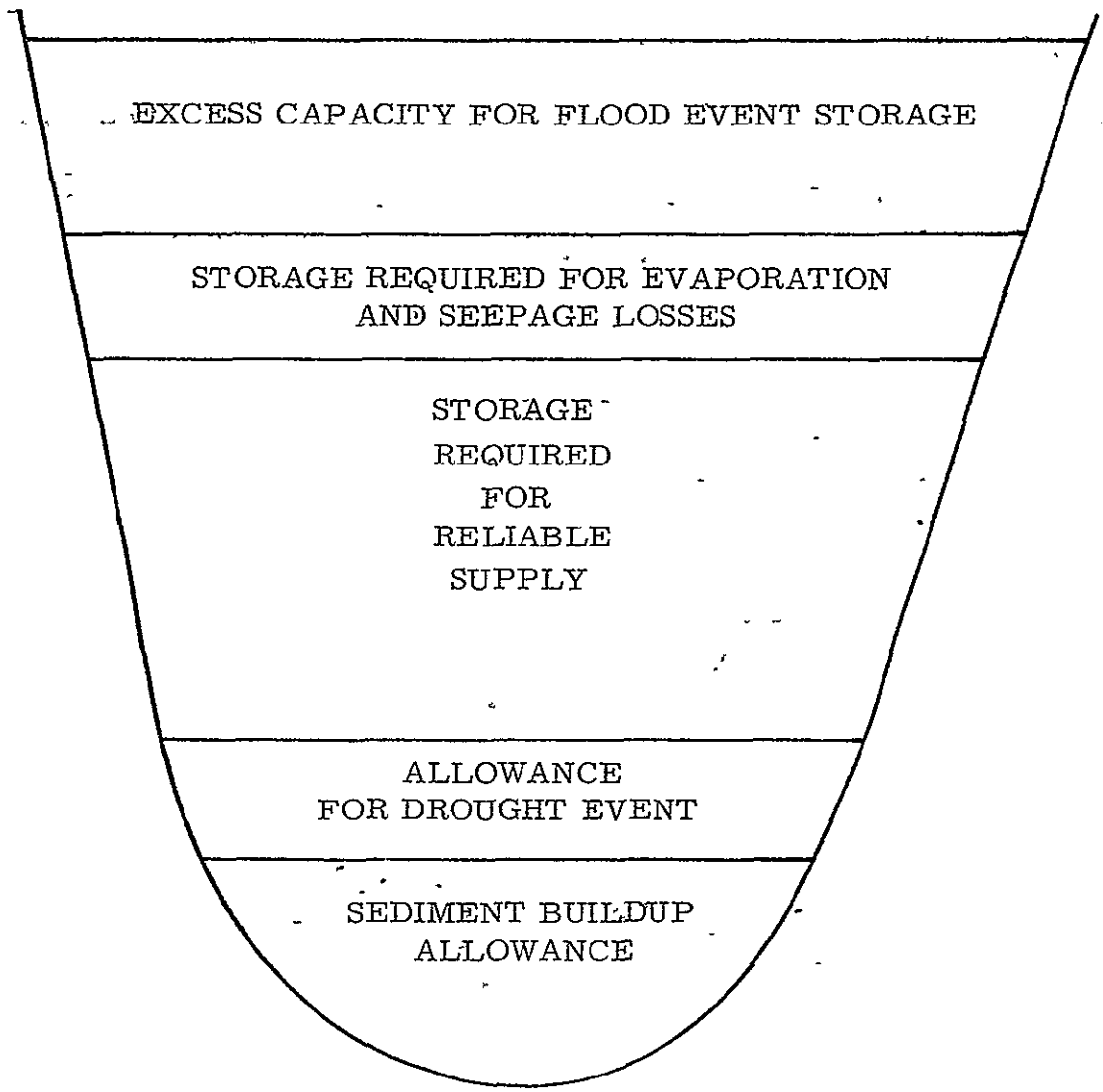
Excess storage required to compensate for ground seepage.

Excess storage required to cope with floods.

Excess storage required to at least partially cope with extreme water shortage or unusual flood events.

As we shall see further on, reservoir storage is becoming increasingly scarce and costly. The planning and management of the excess storage volume is becoming increasingly important.

TYPICAL RESERVOIR DESIGN CAPACITY

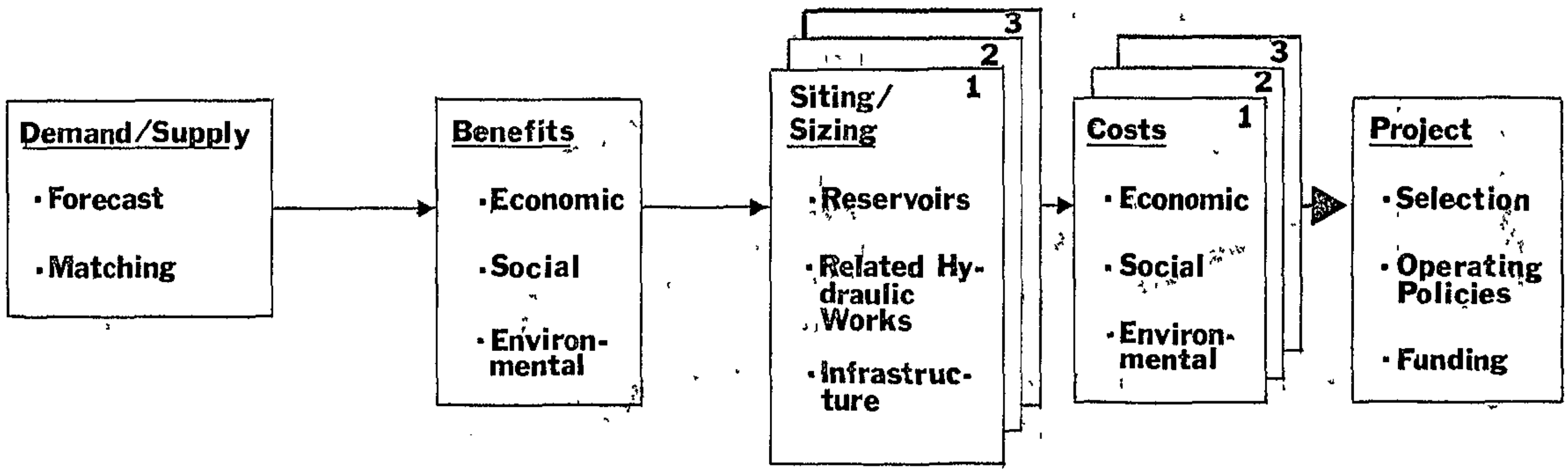


Water regulation projects must, in the U.S., satisfy economic benefit/cost criteria.

During the last decade, social and environmental criteria have acquired increasing significance; their inclusion within overall project criteria is now required.

In most practical cases, more than one physical implementation is possible: several potentially viable reservoir sites are generally available. Thus, several design alternates are chosen and analyzed.

MAJOR WATER REGULATION PROJECT SEQUENCE



Several significant Economic, Social and Environmental factors enter the benefit/cost and impact trade-offs of each alternate implementation of the project.

PRINCIPAL ECONOMIC, SOCIAL, AND ENVIRONMENTAL FACTORS IN WATER REGULATION PROJECTS

PROJECT ECONOMICS

BENEFITS

- Water Supply Value
- Recreation Value
- Power Revenue
- Flood Damage Reduction
- Navigation Value

COST

- Land Loss
- Flow Loss
- Relocation of Population Structures
- Relocation of Public Facilities Services
- Alteration of Taxation Base

SOCIAL IMPACT

- Impact of Influx of Federal State Money
- Impact on Overland Transportation
- Altered Recreation Pattern
- Impact on Historical/ Archeological Factors
- Loss of Goodwill of Relocated Industries
- Alteration of Community Regional Growth Cohesion
- Alteration of Scenic Esthetic Value
- Impact on Employment Base

ENVIRONMENTAL IMPACT

- Fish / Wildlife
- Air
- Water
- Noise
- Forest/ Plant Life Ecology
- Altered Downstream Revenue / Environment

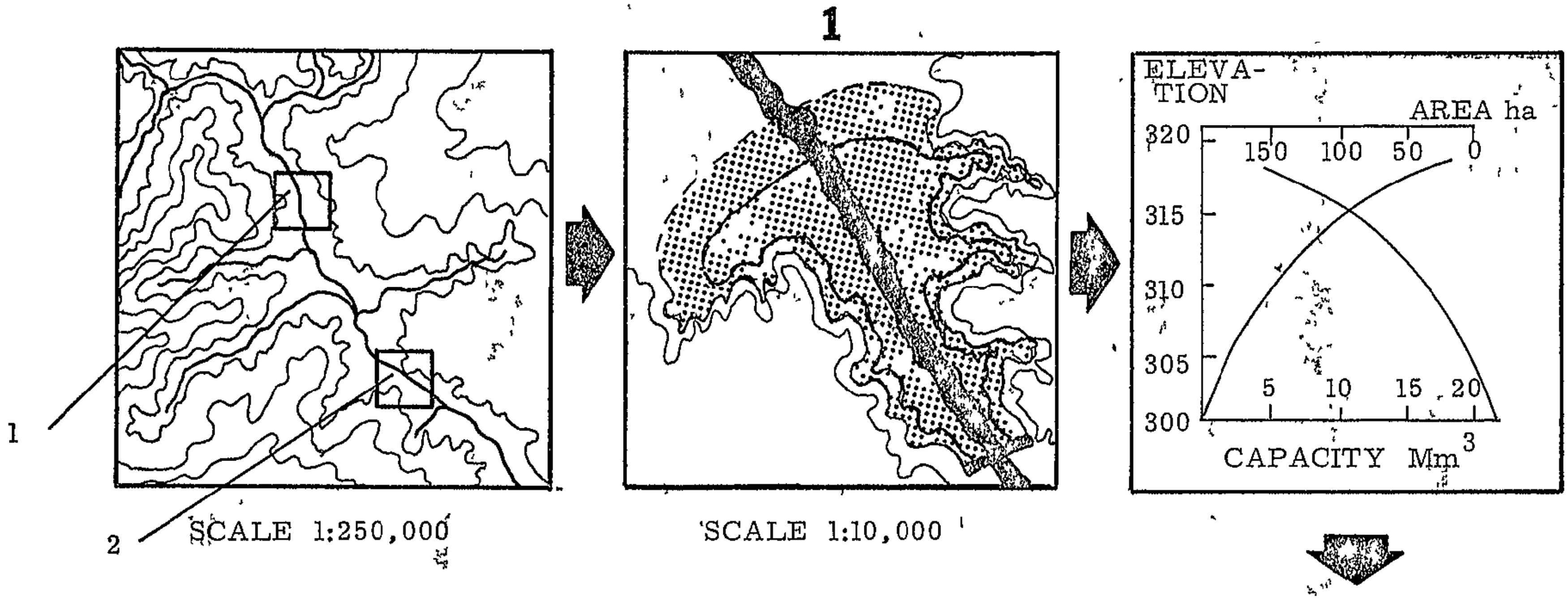
In the conventional reservoir siting procedure, promising candidate sites are initially selected, based upon topographic and geographic characteristics.

Each site displays characteristic relationships between capacity inundated area and water height, which are functions of the topography. Similarly, the cost of damming is influenced by topography and the site's geology. Evaporation and leakage losses are influenced by geography, climate, topography and soil characteristics.

Many of the environmental impacts are affected by the extent of the flooded area.

The physical selection of reservoir sites requires availability of topography on regional scales (1:1,000 to 1:250,000), and on local scales (1:50,000 to 1:10,000). Local scales are obtainable from aircraft-borne stereoimagery. Regional scales could be obtained from stero satellite imagery.

The assessment of the environmental impact, and of portions of the economic and social impact, is amenable to current-capability remote sensing.



- COSTS
- BENEFITS
- SOCIAL INPACT
- ENVIRONMENTAL IMPACT

ALTERNATIVE PROJECT 1

RESERVOIR SITING PROCEDURE

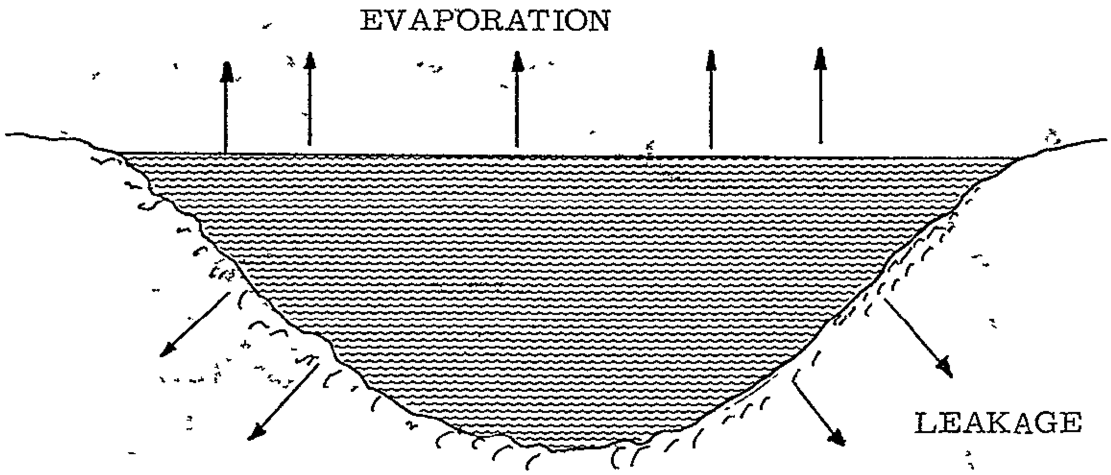
As the water volume in a reservoir increases, so do the surface and the wetted areas.

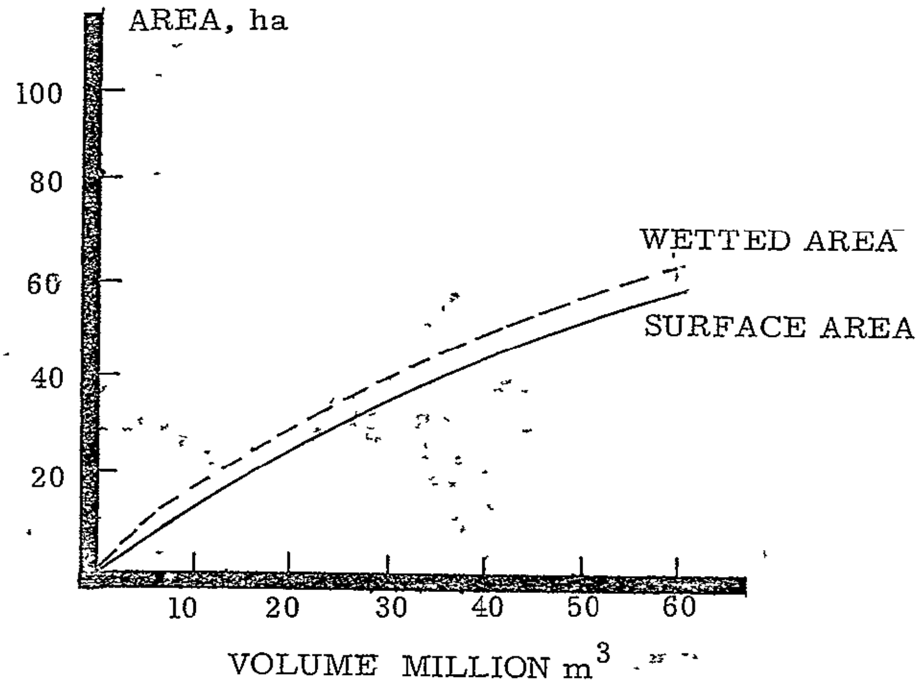
Surface area gives rise to evaporation losses: wetted area to leakage losses.

When these losses equal, or reach an appreciable fraction of the inflow, further increases in reservoir capacity are not economically justified.

There is thus a maximum economic size of reservoir which depends upon the climate, soil characteristics and structure, and upon the reservoir's geometry.

RESERVOIR LOSS DRIVERS



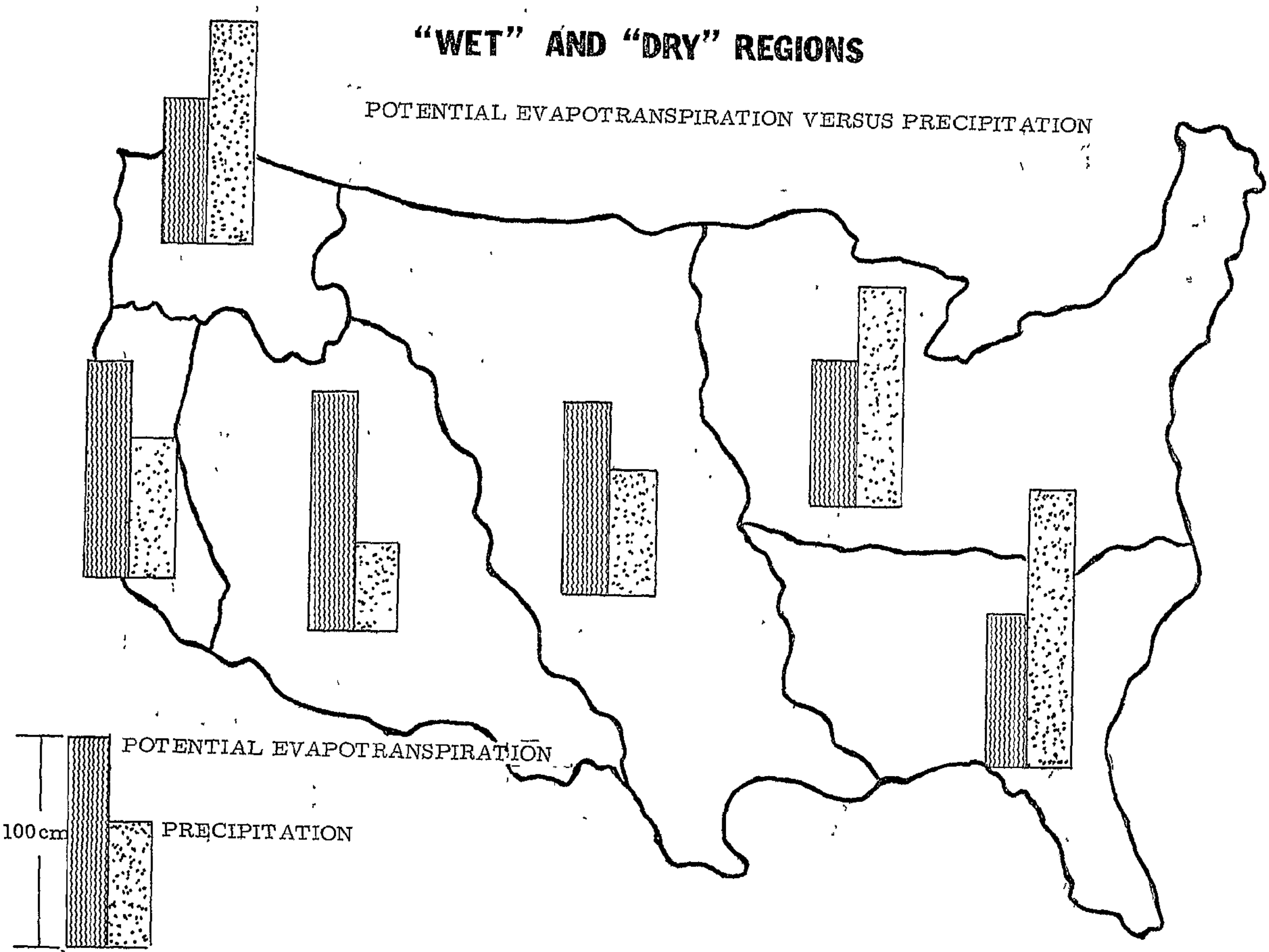


The evaporation loss is particularly critical in those regions where the potential evapotranspiration -- defined as the evaporation from a free water surface -- exceeds the rainfall.

Under these conditions, the reservoir's water surface will lose more water than is contributed by the rainfall. The difference constitutes a loss which must be supplied from the incoming flow.

For large reservoirs in arid U.S. regions, the deficiency between rainfall and evaporation can cause yearly losses as high as 6% of reservoir capacity.

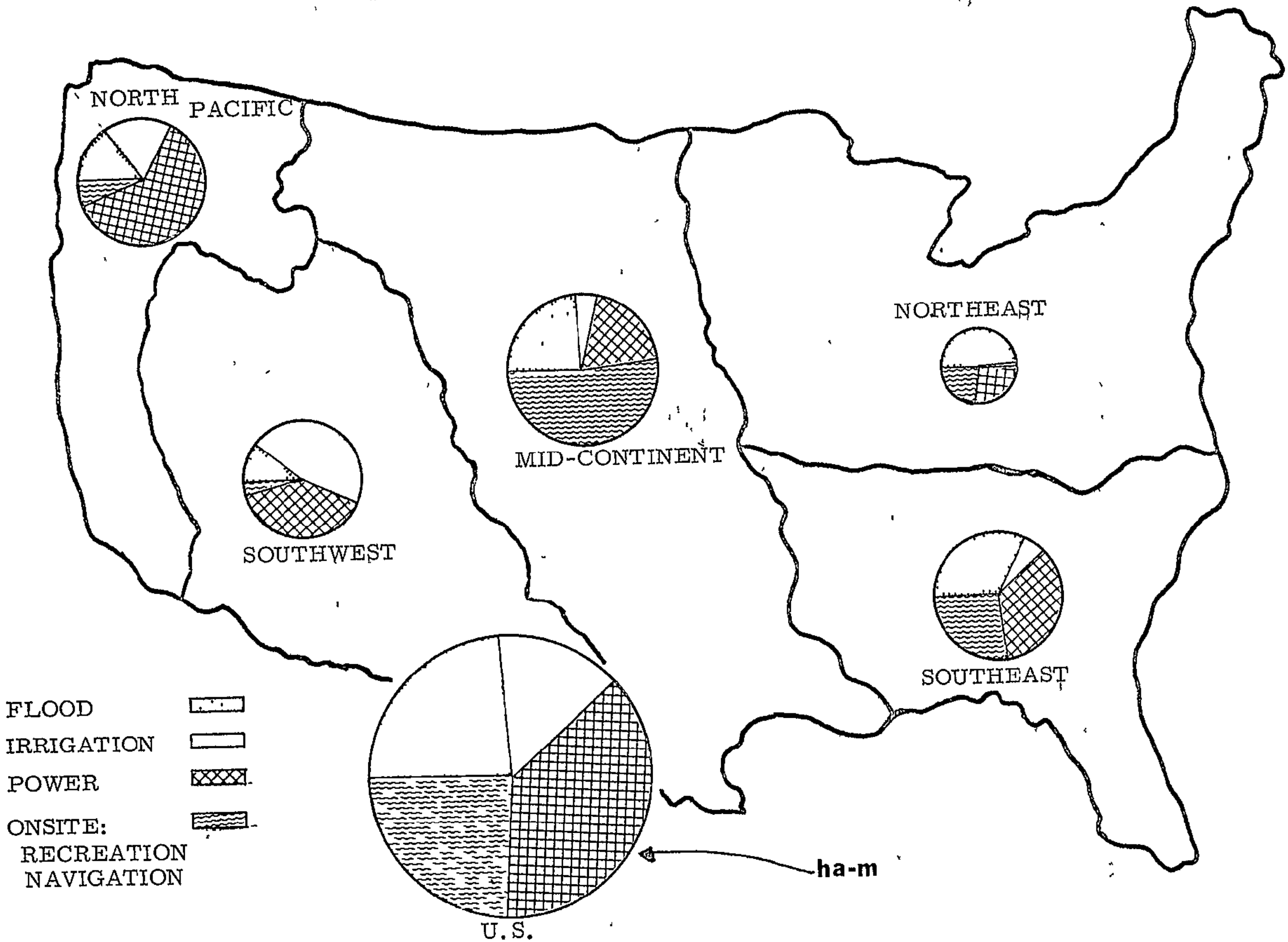
More important is the uncertainty of present evaporation models, estimated at approximately 30% for 5% confidence. This results in an uncertainty in optimal reservoir size of 2% for the larger reservoirs. As can be deduced from the cost figures which follow, the corresponding cost penalty can range as high as $1.5 million for large reservoirs.


"WET" AND "DRY" REGIONS
POTENTIAL EVAPOTRANSPIRATION VERSUS PRECIPITATION
POTENTIAL EVAPOTRANSPIRATION
100 cm
PRECIPITATION

Current U.S. reservoir capacity is allocated among different uses. Storage for cooling and pollution dilution is still quite limited.

Total current U.S. reservoir capacity is 23 Million ha-m.

DISTRIBUTION OF STORAGE CAPACITY

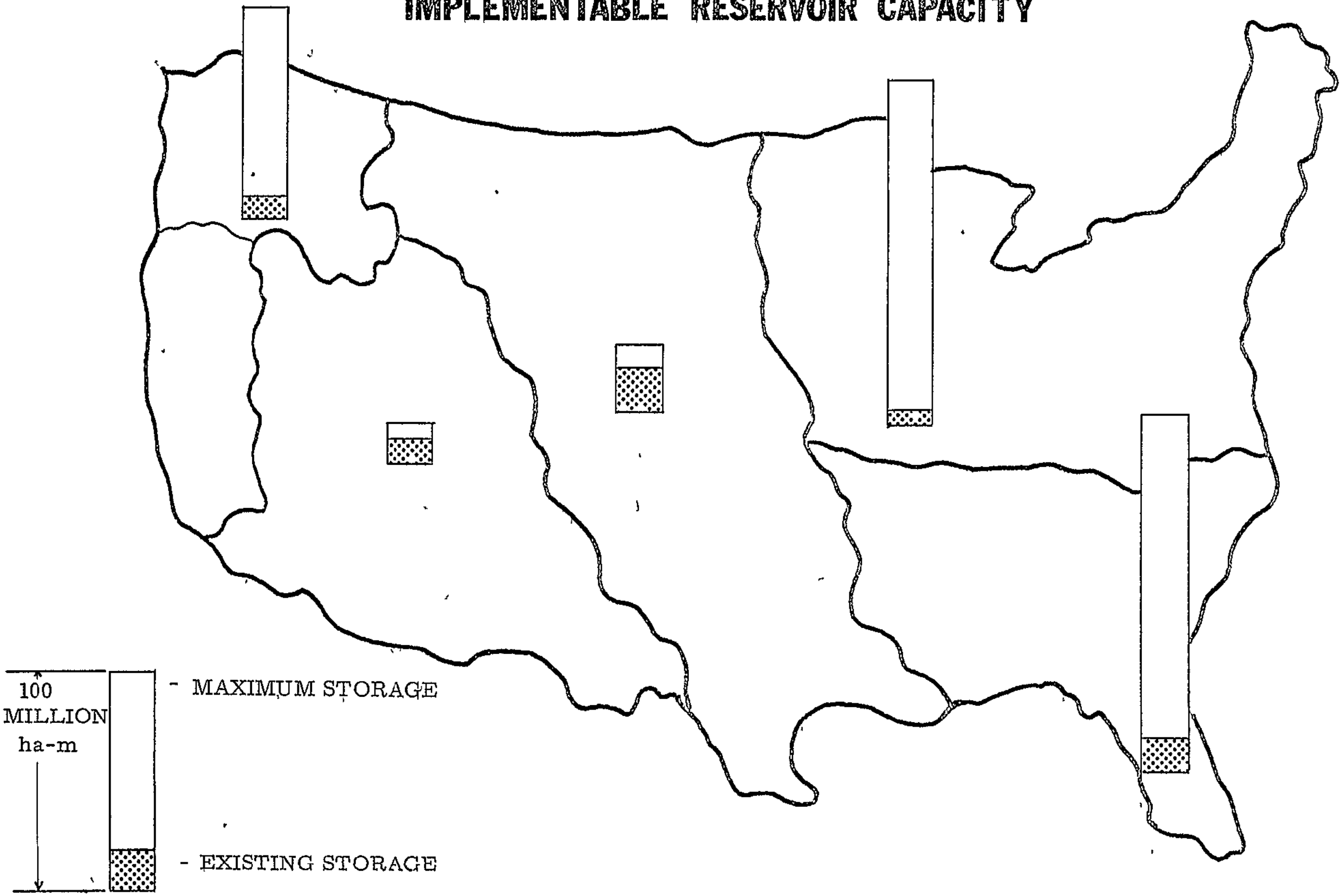


The U.S. reservoir capacity implemented so far is but a fraction of the total which is effectively utilizable. However, most of the better U.S. reservoir sites have already been exploited.

This means that additional capacity must be paid for at higher prices than those already paid for the "best" sites.

How does one go about calculating this increased cost?

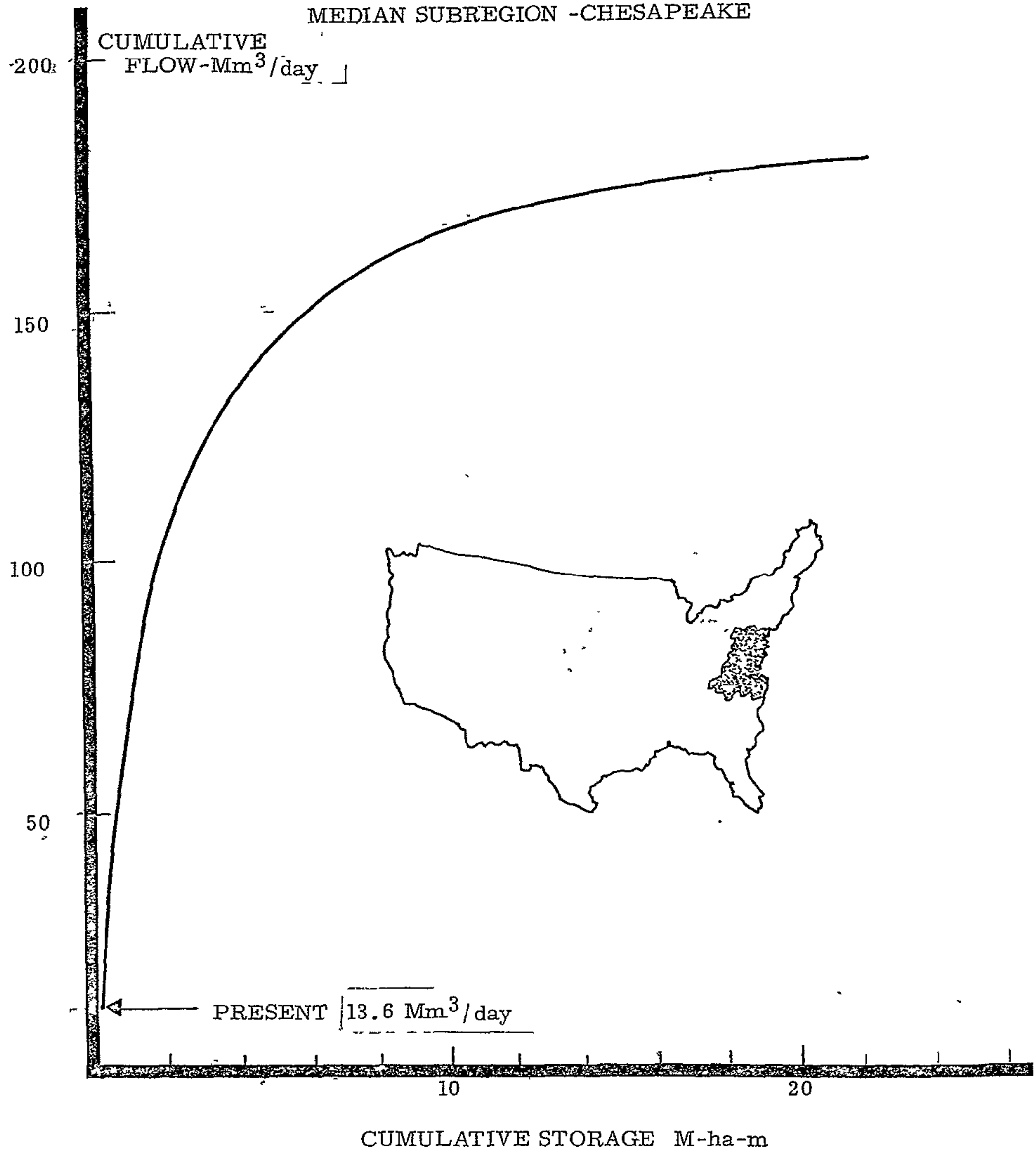
EXISTING VERSUS MAXIMUM IMPLEMENTABLE RESERVOIR CAPACITY



First of all, each region possesses a characteristic storage-flow relationship which is a function of the statistical variability of the region's watercourses.

The storage-flow relationship expresses how much reservoir storage must be provided to smooth out the river's variability to a specified reliable flow.

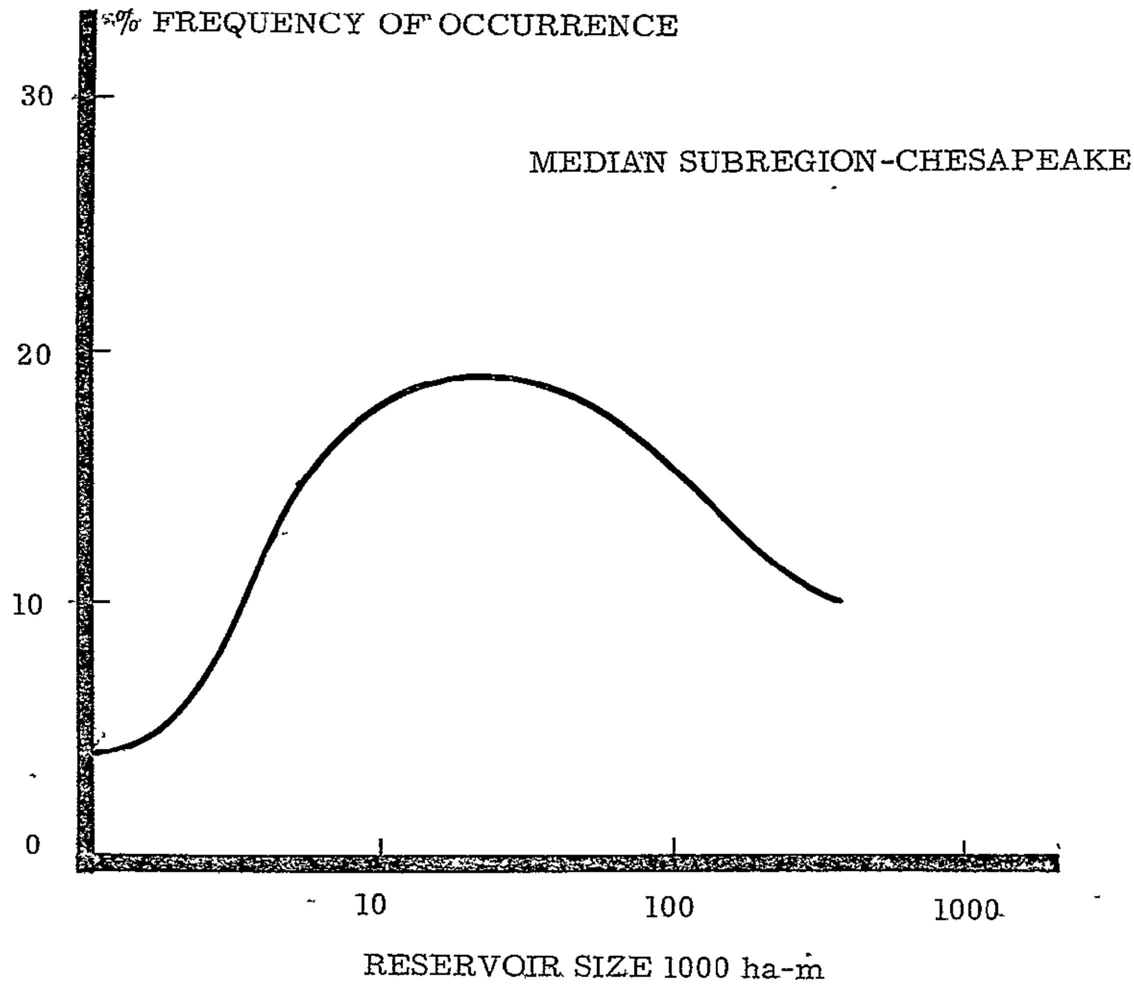
STORAGE REQUIRED TO PROVIDE RELIABLE (98%) FLOW



Next, each region possesses a distribution of potential reservoir storage, which is a function of the region's geography and topography.

Some regions possess many small sites, others possess distributions featuring more of the larger sites.

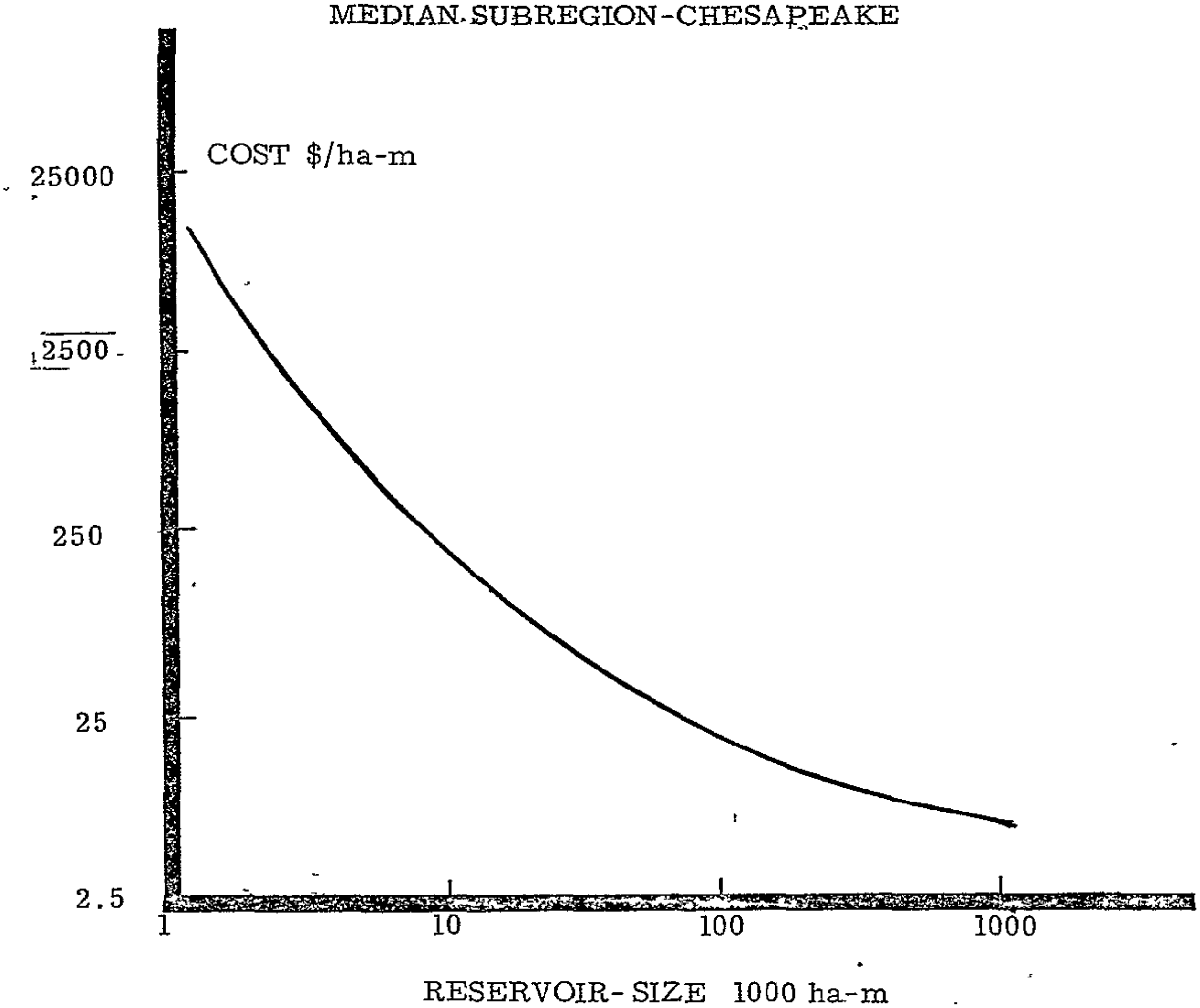
DISTRIBUTION OF RESERVOIRS BY CAPACITY



Third, the cost of developing reservoirs varies within each region as a function of its topography and geography. As a general trend, small reservoirs cost more per unit storage capacity than large ones.

COST OF WATER STORAGE VERSUS RESERVOIR SIZE

MEDIAN-SUBREGION-CHESAPEAKE

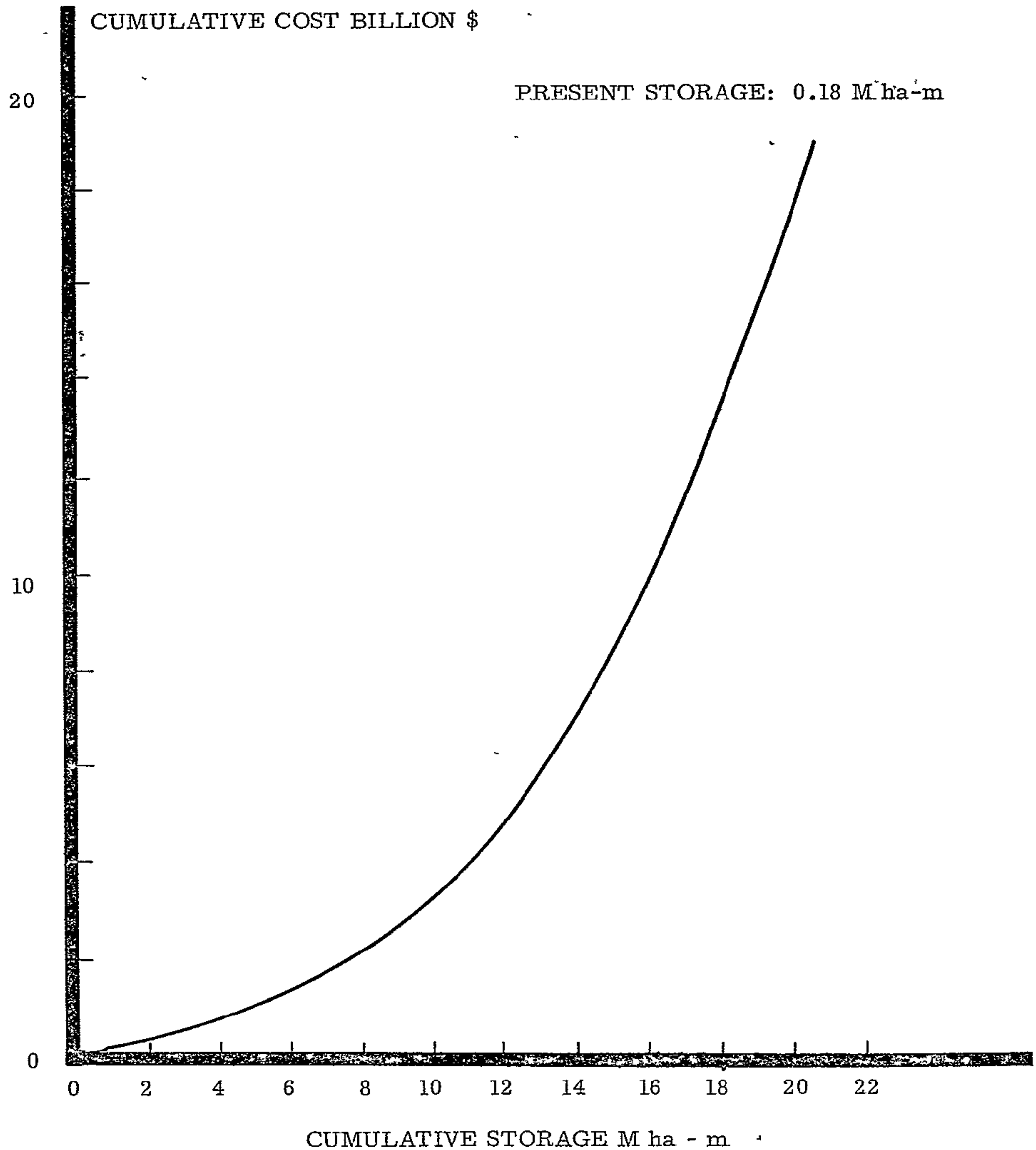


The combination of the two previous relationships -- Distribution of Reservoirs by Capacity, and Cost of Storage Versus Reservoir Size -- for any region, yields the cumulative cost to develop reservoir capacity within that region.

The above two relationships, and the corresponding cumulative costs, vary significantly among regions.

CUMULATIVE COST TO DEVELOP RESERVOIR CAPACITY

MEDIAN SUBREGION-CHESAPEAKE



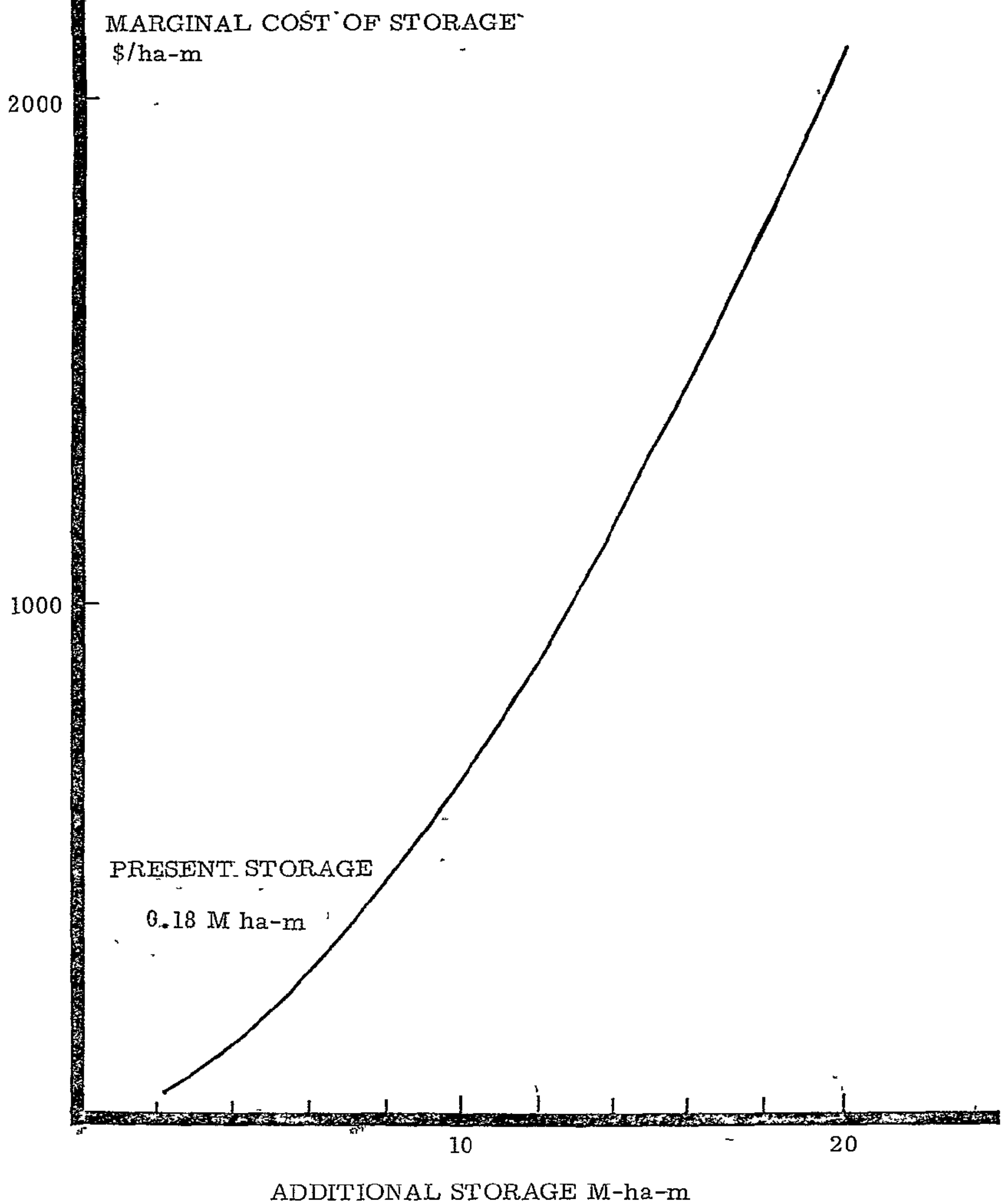
The marginal cost is the incremental cost of developing additional reservoirs over and above the present level of storage capacity.

Note that the marginal cost increases sharply as the level of reservoir development increases.

This reflects the previously noted fact that the more cost/effective reservoirs have been developed first.

COST PENALTY OF ADDING RESERVOIR CAPACITY

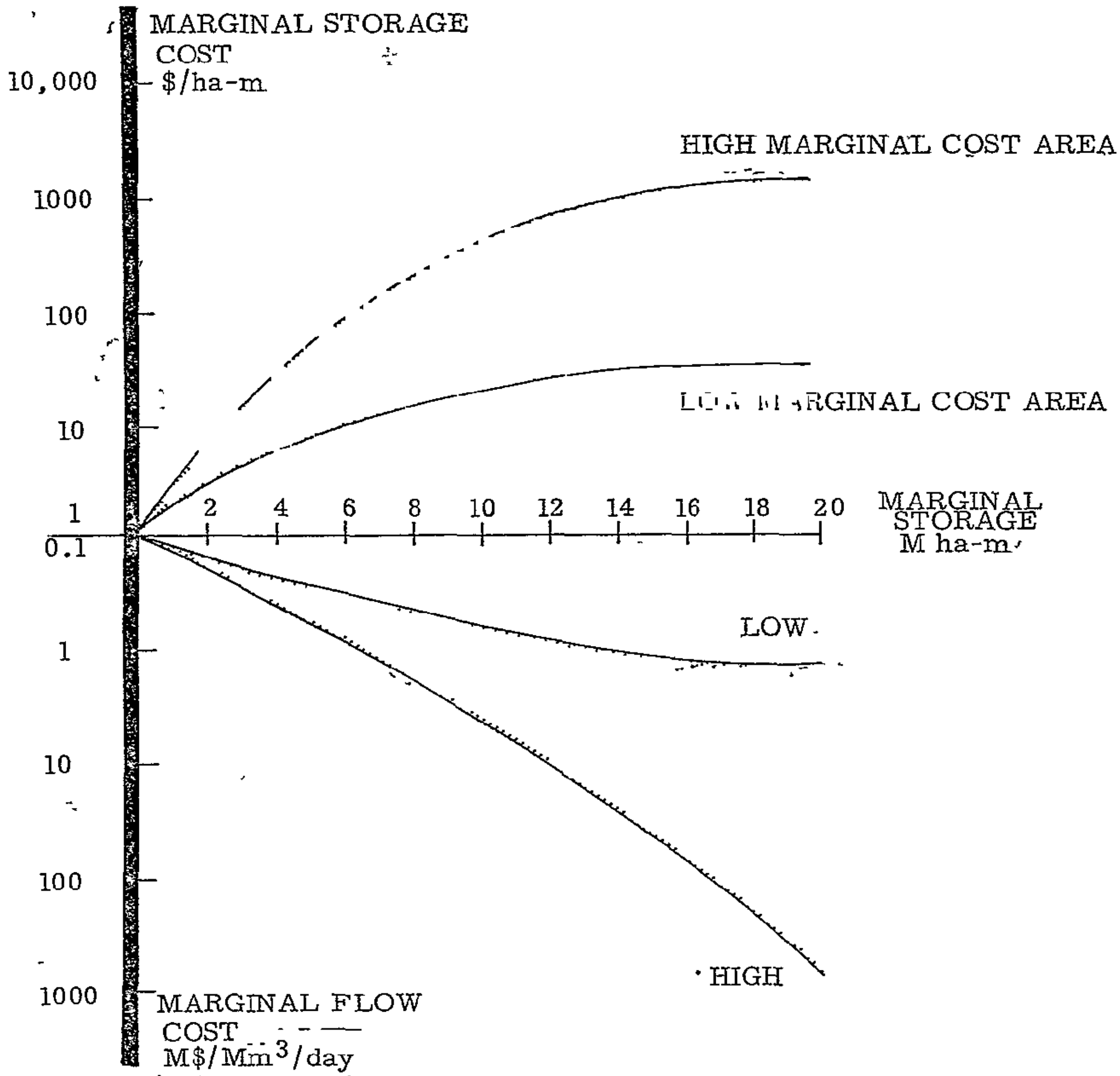
MEDIAN SUBREGION-CHESAPEAKE



The marginal cost of reservoir development, and consequently of flow augmentation, varies by two orders of magnitude among U.S. regions.

RANGE OF MARGINAL STORAGE/FLOW COSTS TO PROVIDE INCREASE IN MARGINAL RESERVOIR STORAGE IN THE U.S.

98% AVAILABILITY

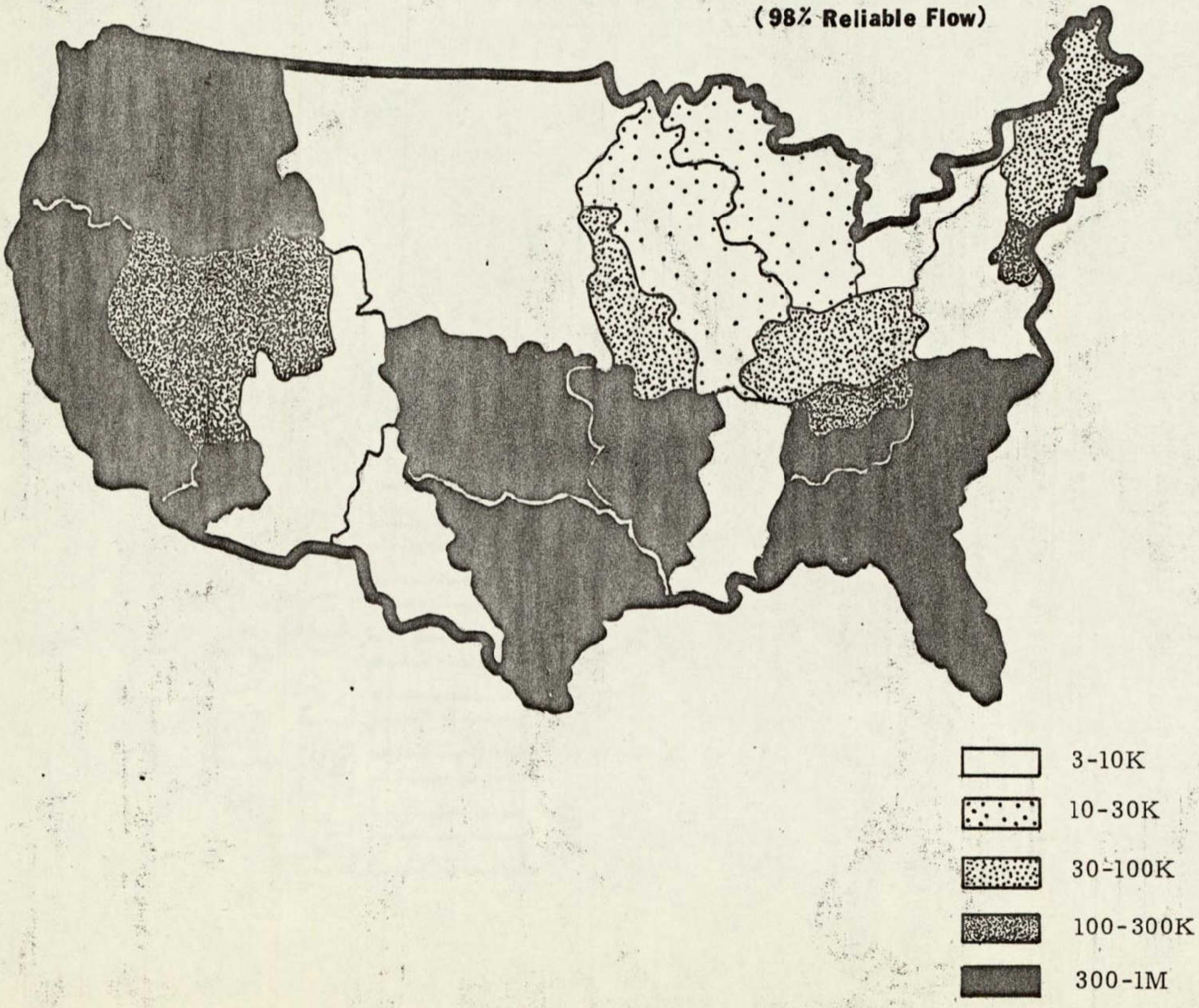


A means to normalize waterworks development costs between regions is in terms of the costs required to satisfy a common percentage increase in the demand.

The opposite chart expresses the marginal costs, by region, required to increase the 98% reliable flow by 1%.

RESERVOIR DEVELOPMENT COST TO ACHIEVE 1% FLOW INCREASE

(98% Reliable Flow)

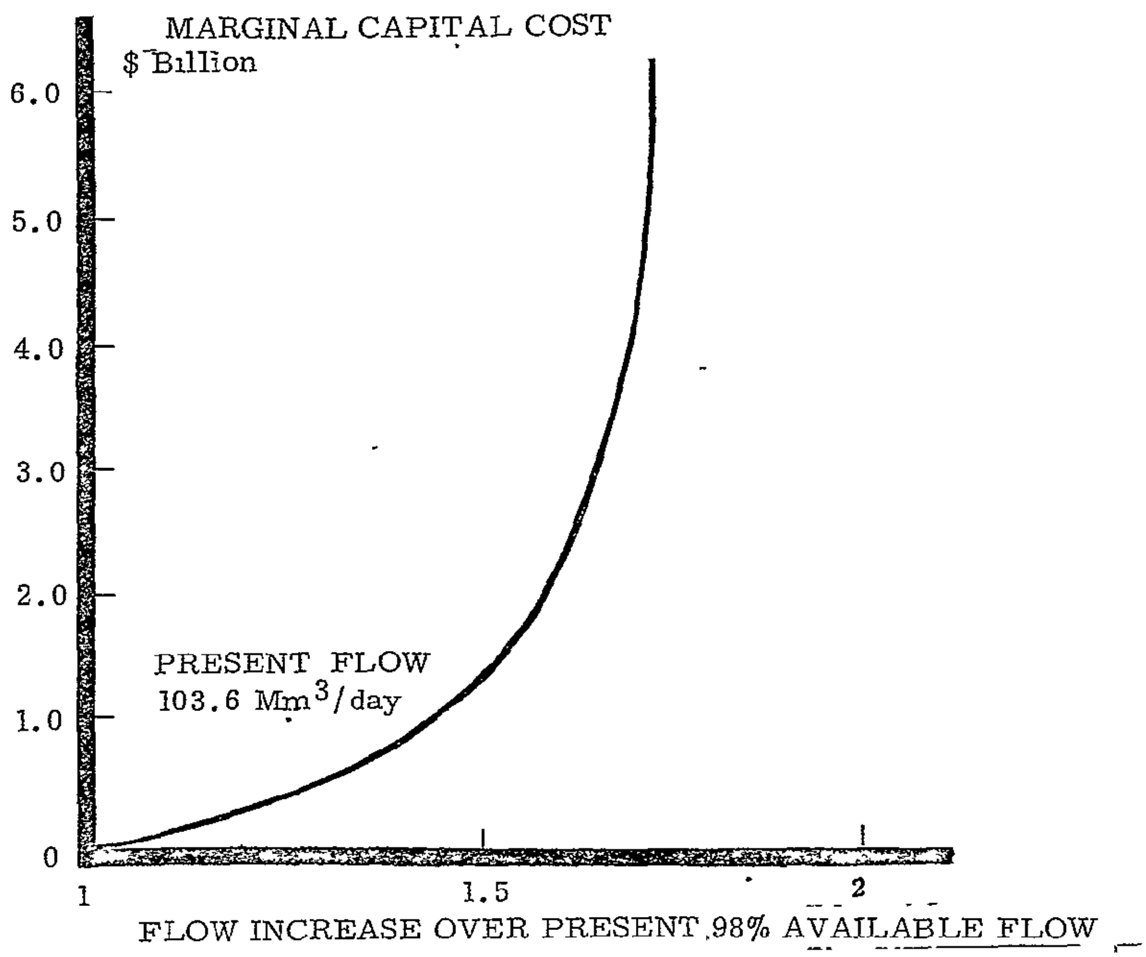


The cost of generating flow increases much more rapidly than the increase in flow.

Shown opposite is the case for California, one of the "expensive" regions.

RESERVOIR DEVELOPMENT COST

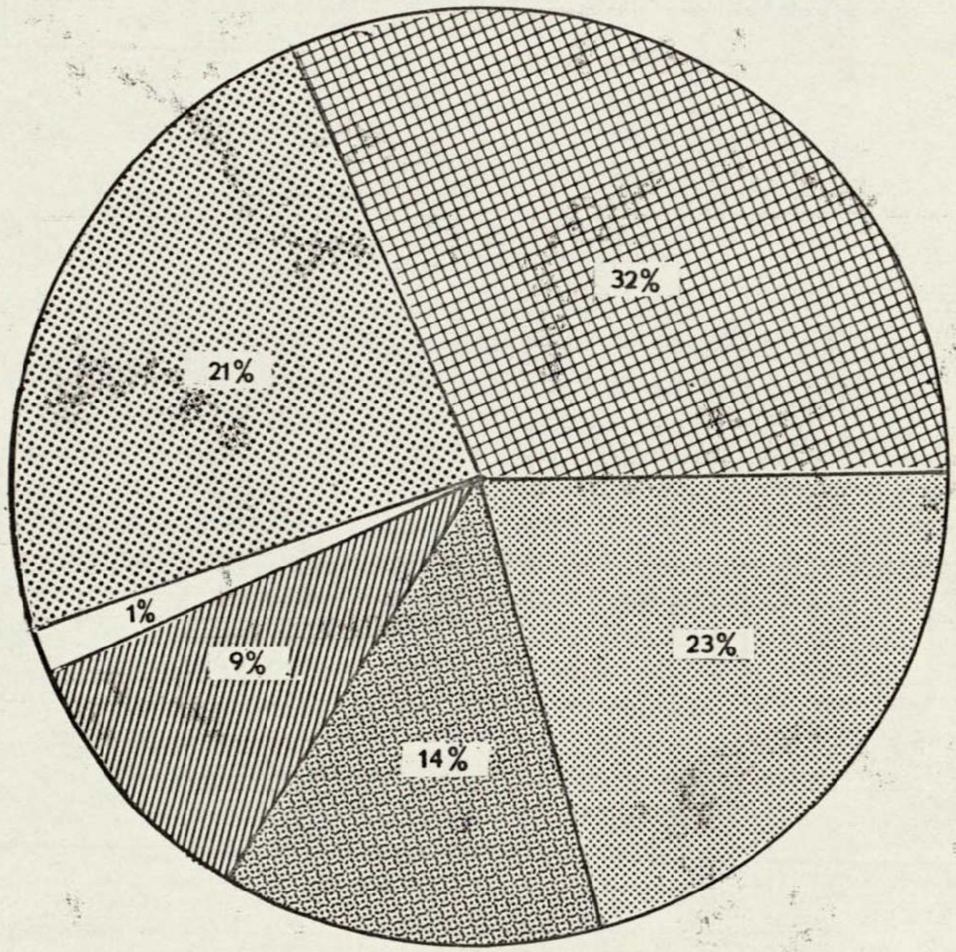
CALIFORNIA



3.3 INDUSTRIAL WATER REQUIREMENTS

The manufacturing industry is generally considered a significant user of water.

INDUSTRIAL USE OF WATER
WITHDRAWALS, YEAR 1970



PRIMARY METALS 32%

CHEMICALS 23%

PETROLEUM/COAL 14%

FOOD 9%

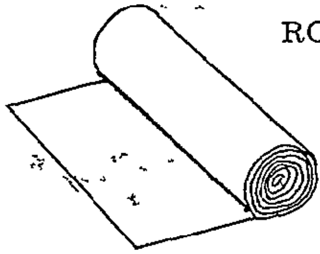
LEATHER 1%

OTHER 21%

TOTAL INDUSTRIAL WITHDRAWAL:
130 Mm^3/day

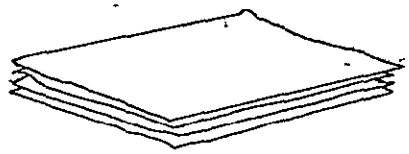
This is because the quantities of water required to produce a unit quantity of most industrially manufactured products are large.

WATER DEMAND FOR INDUSTRIAL PRODUCTS

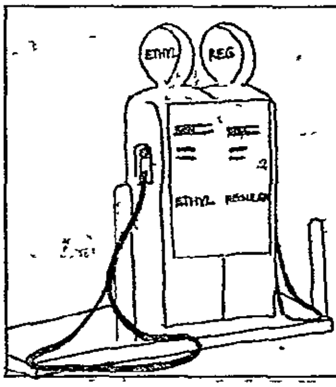


ROLLED STEEL
420

AVERAGE
ALL
PRODUCTS
90-154



PAPER
210

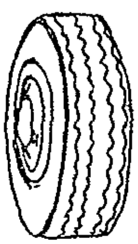


GASOLINE
7-40

SUGAR
5-110

ACETIC ACID
530-1280

MEAT
22



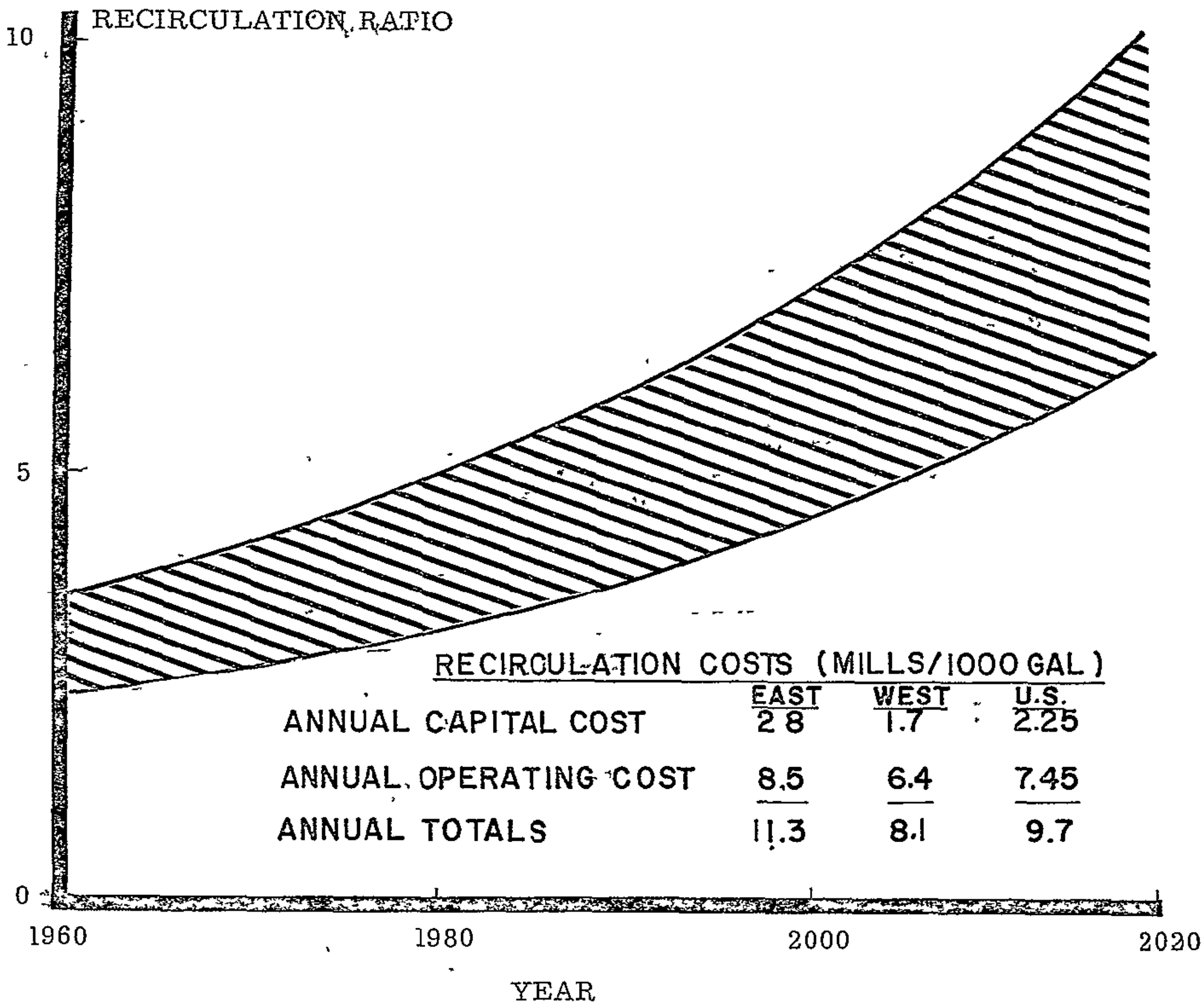
SYNTHETIC
RUBBER
110-3520

TONS OF WATER PER TON OF FINAL PRODUCT

In reality, water usage by the manufacturing industry is modest when compared to the total demand. The reason is that the manufacturing industry employs considerable levels of recirculation. Recirculation practice will further increase in the future.

Recirculation is generally cheaper than the acquisition of new water.

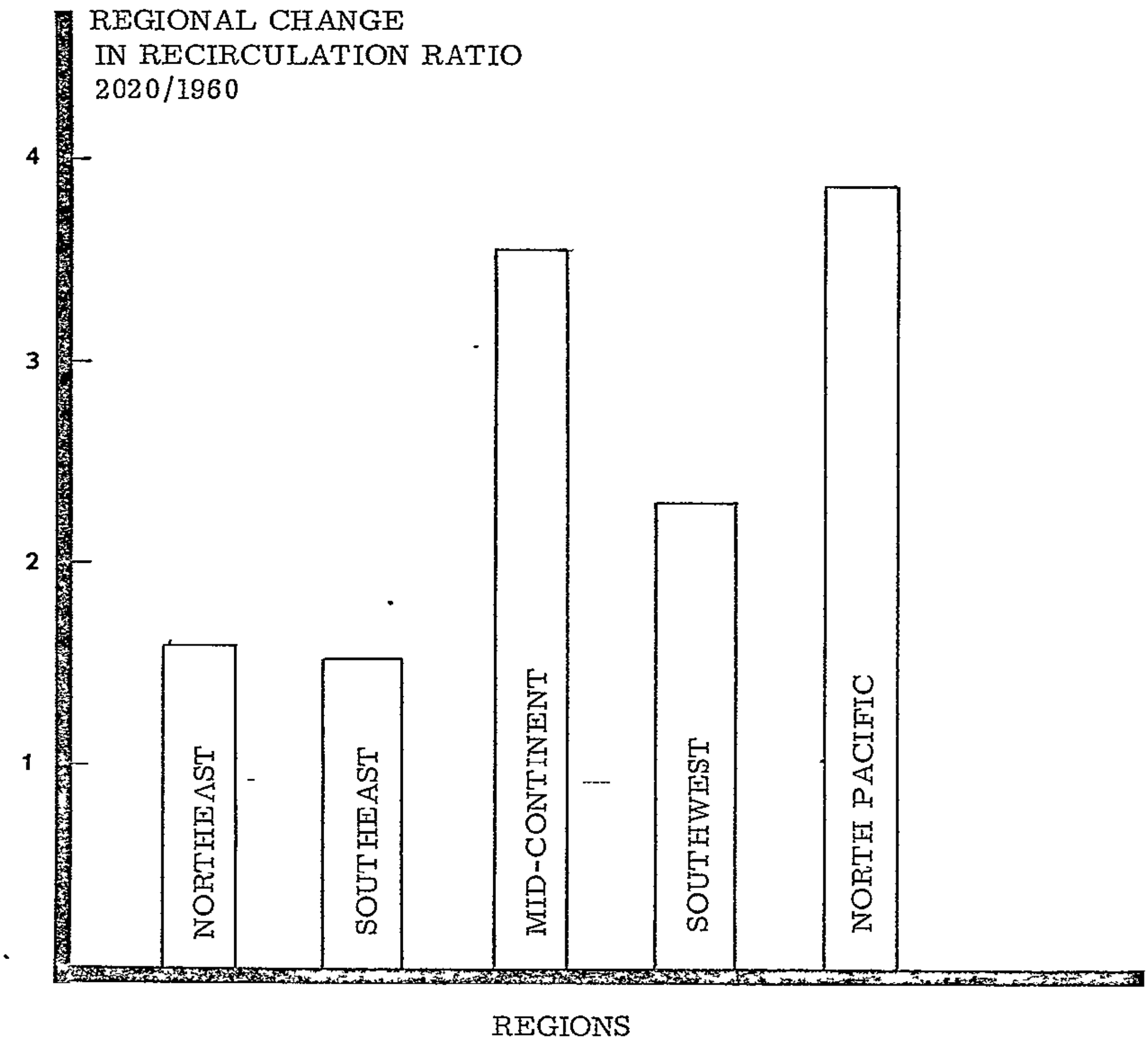
PROJECTED GROWTH OF U.S. INDUSTRIAL WATER RECIRCULATION PRACTICES



As would be expected, the recirculation ratio does and will continue to vary as a function of each region's water availability.

The point is that the manufacturing industry lends itself to concentrated application of water-conservation practices. Thus, industrial water use can and will be maintained within bounds.

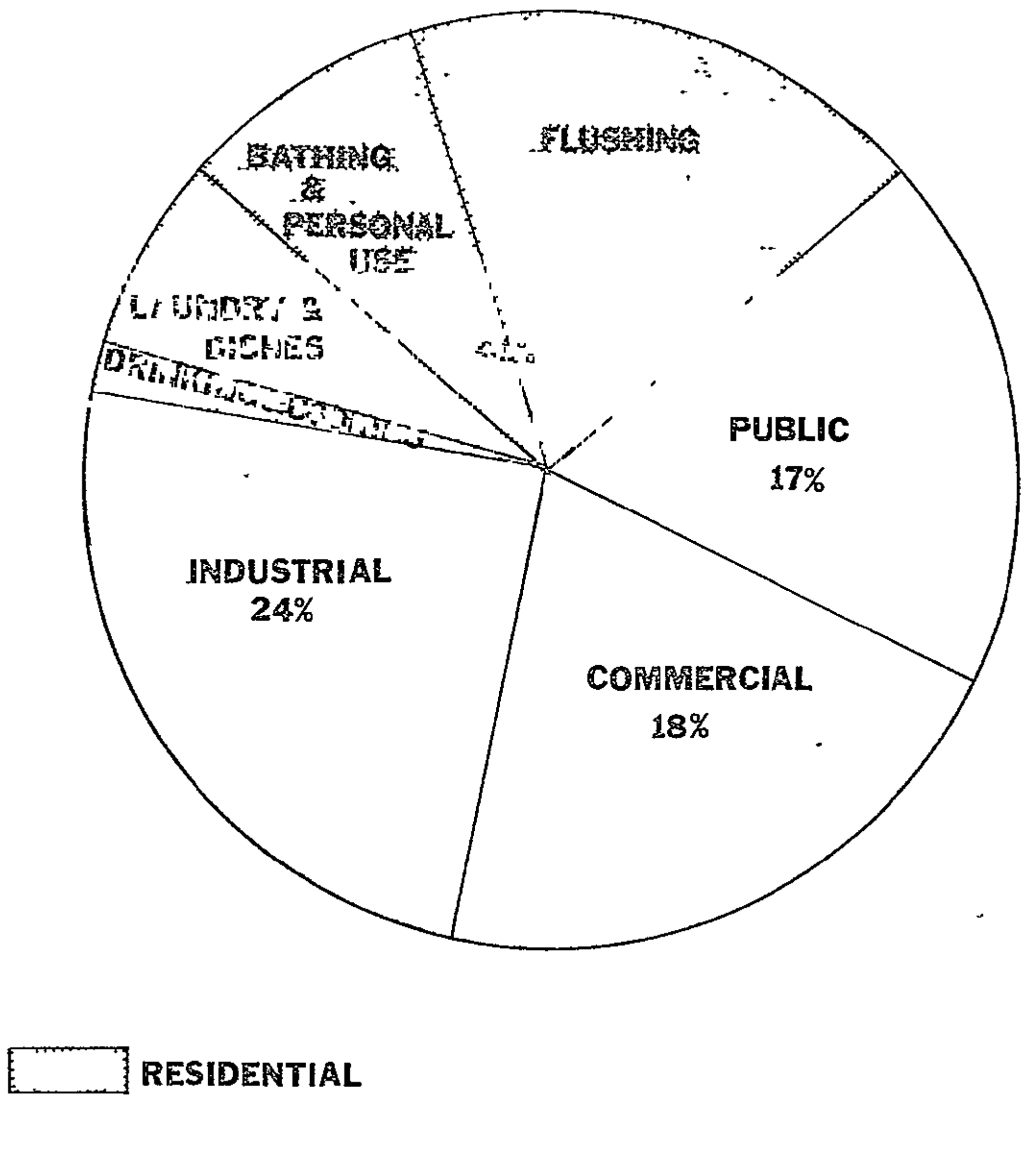
REGIONAL RECIRCULATION PROJECTIONS



3.4 URBAN WATER REQUIREMENTS.

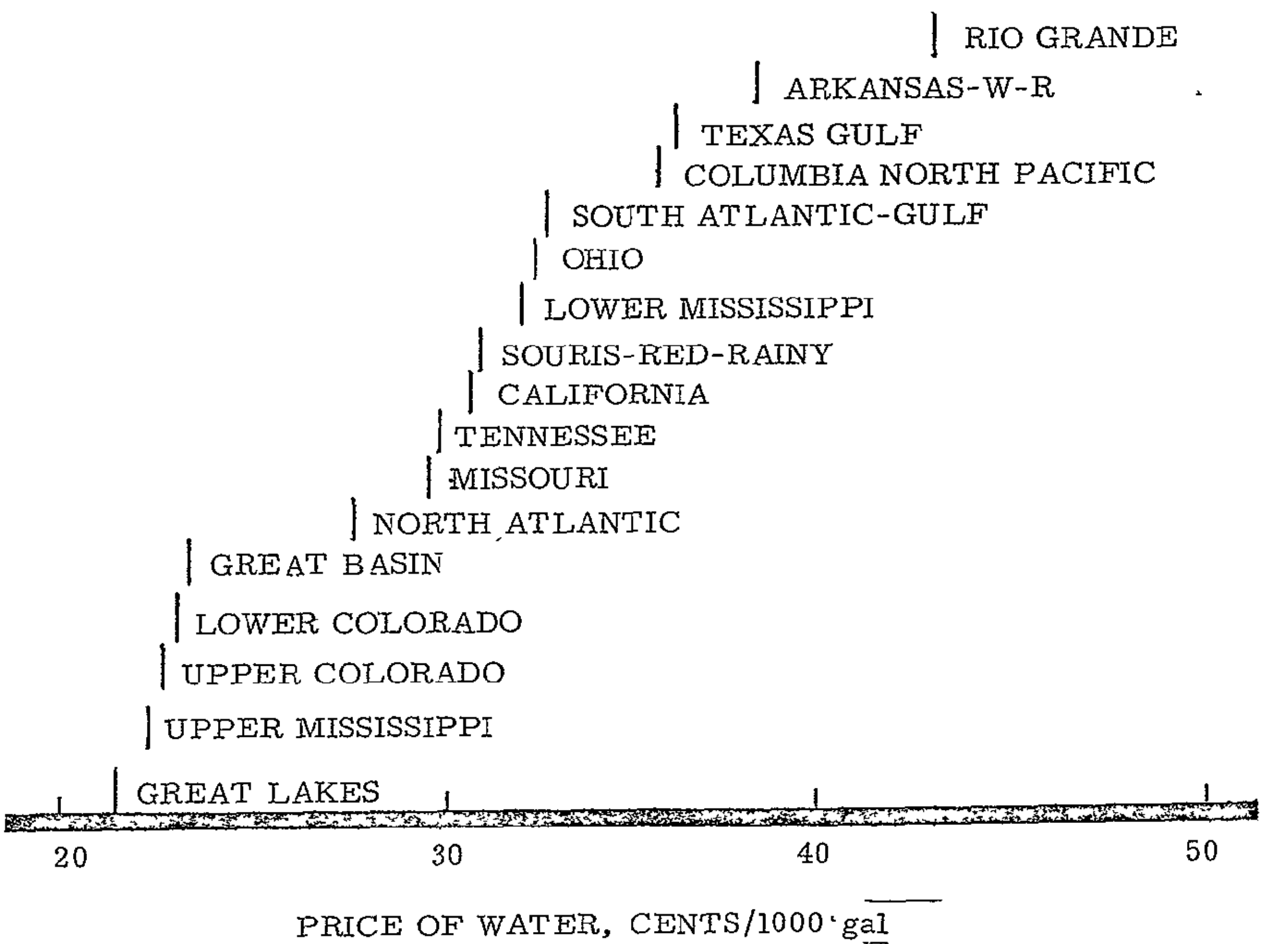
Municipal water uses at present represent a relatively small fraction of U.S. withdrawal demand, but feature high levels of consumption and the highest prices.

URBAN WATER DEMAND



The average prices paid by consumers for municipal water vary from region to region.

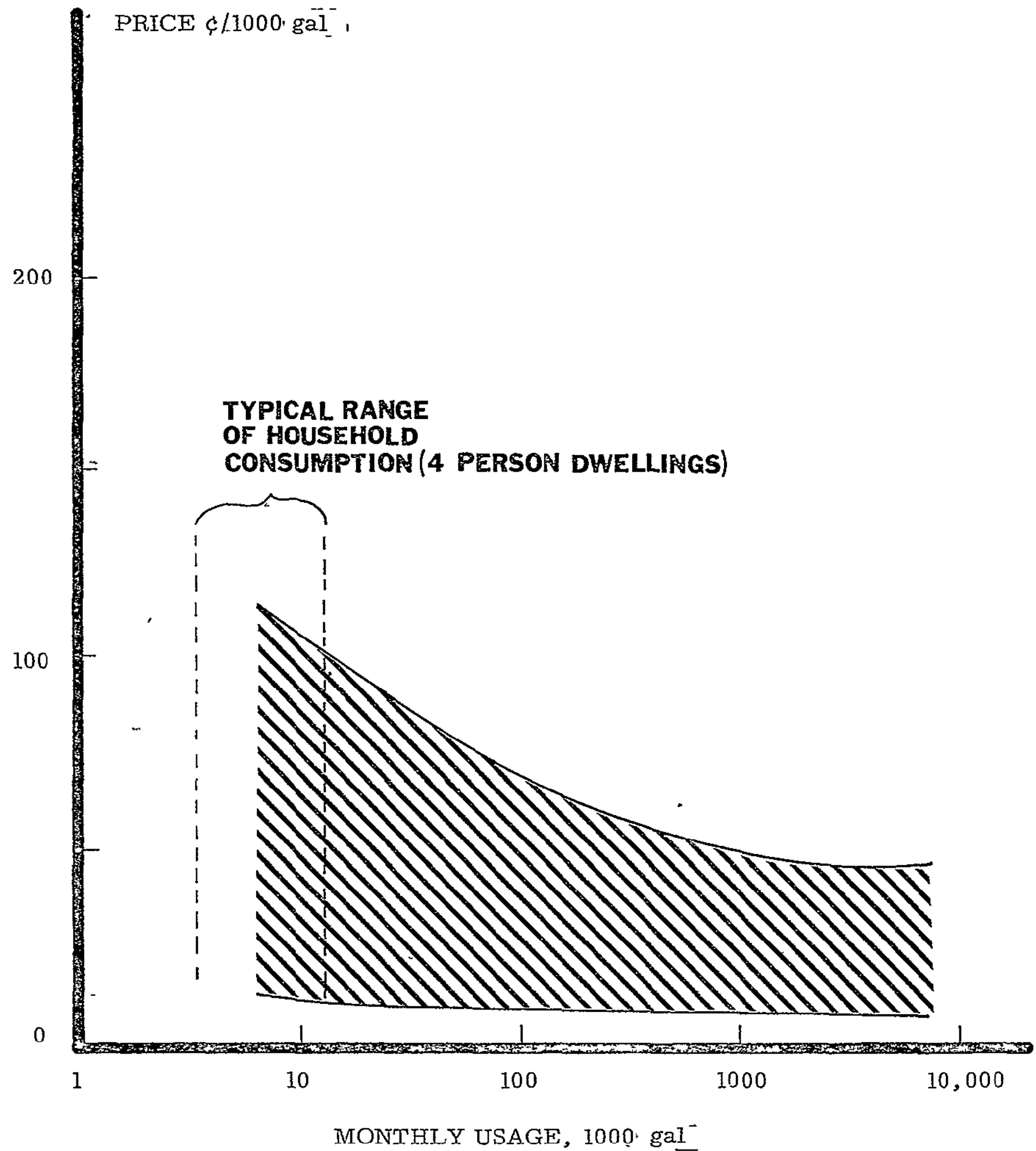
AVERAGE PRICES OF MUNICIPAL WATER



They also vary significantly as a function of the quantity of water consumed. The principal beneficiary of the lower pricing for high quantities is that portion of industry located within urban water distribution systems.

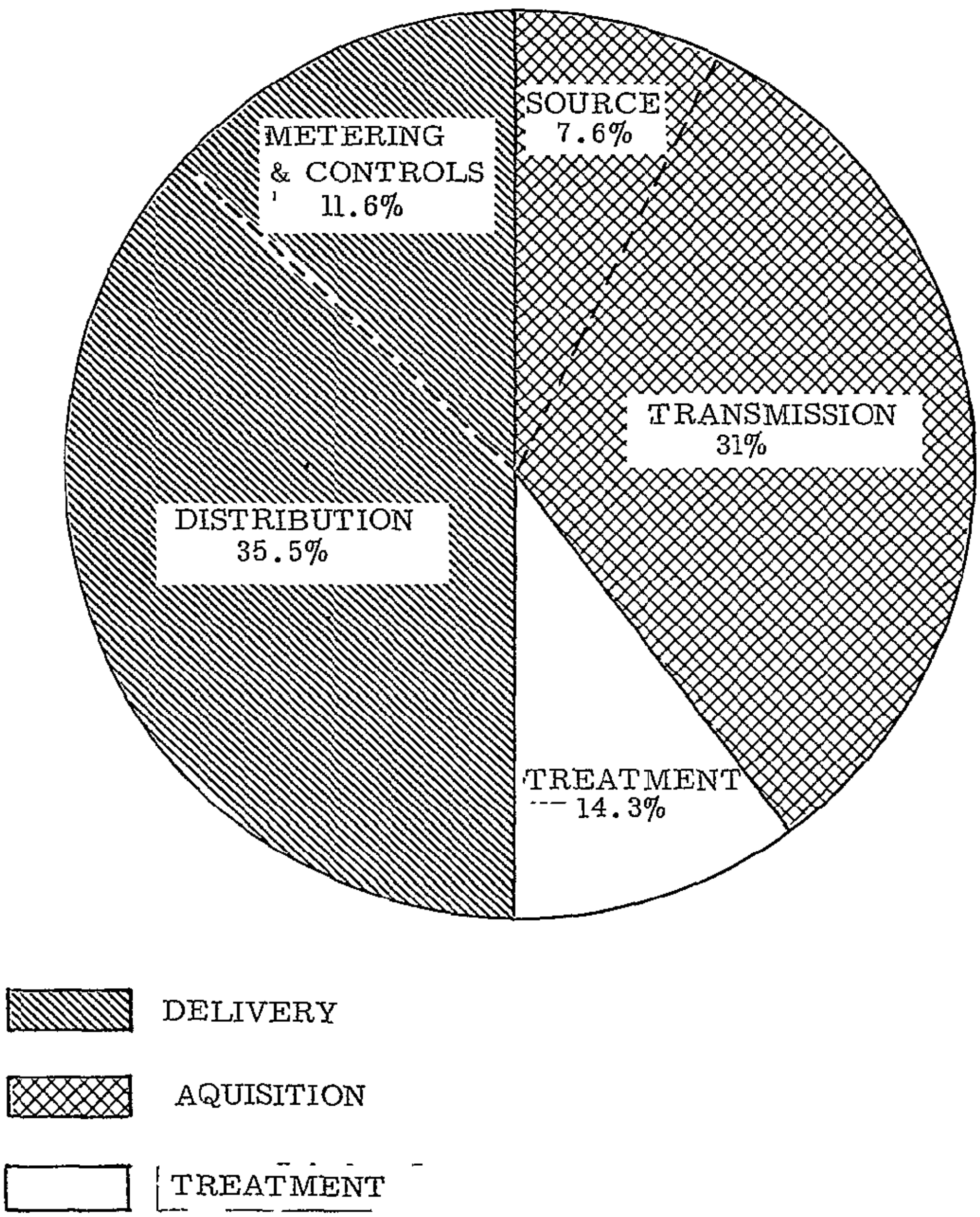
PRICE-DEMAND OF CITY WATER

(SURVEY OF 400 CITIES)



Part of the high cost of municipal water relative to other water uses is attributable to its high quality requirements and the elaborate capillary distribution system.

AVERAGE PERCENTAGE DISTRIBUTION OF CAPITAL COSTS FOR WATER SYSTEMS



3.5 WATER REQUIREMENTS FOR POLLUTION DILUTION

Municipal outflows act as carriers and solvents for household, commercial and industrial wastes. Thus, the outflow of municipal water is a major cause of waterways pollution. A not indifferent fraction of this waste-carrying water is discharged into open waterways without treatment. Primary treatment consists in the removal of suspended material: in the process, some BOD is removed. Secondary treatment adds biologic digestion, such as by activated sludge, to primary treatment.

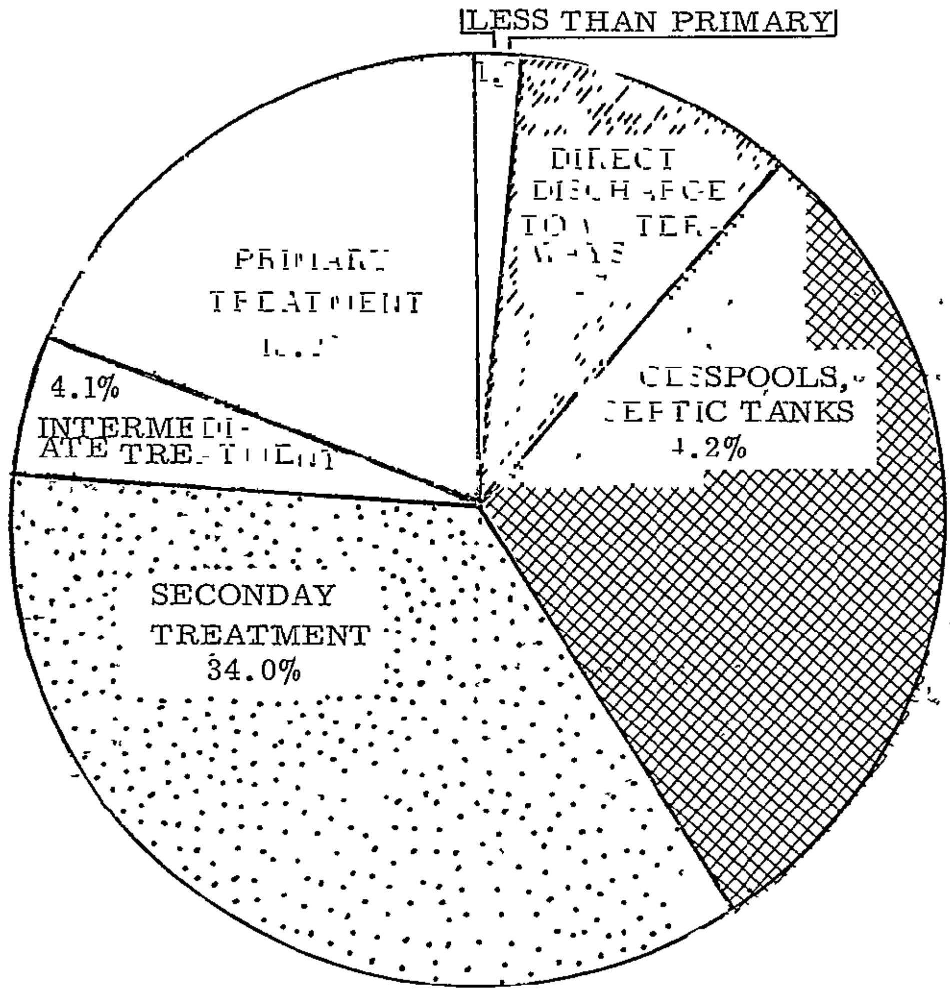
Tertiary treatment, in addition to the first two effects, removes nutrients such as phosphates, to inhibit eutrophication of the waterways.

Average performance levels of waste treatment installations are:

	Suspended Solids Removal	BOD Removal
Primary Treatment	50-70%	25-50%
Secondary Treatment		50-75%
Tertiary Treatment		85-95%

SEWAGE TREATMENT IN THE U.S.

(% OF 1970 TOTAL POPULATION)



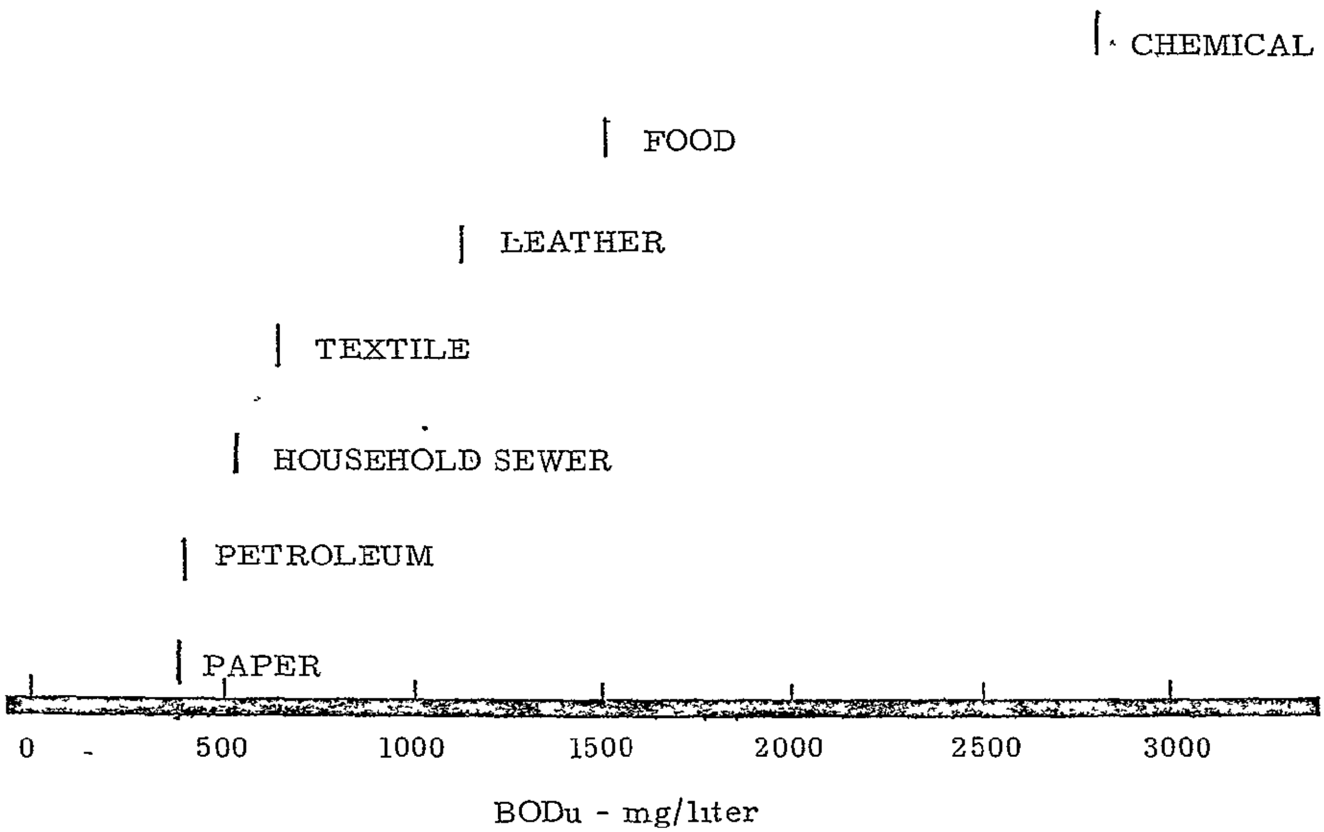
Each industrial or household activity has associated with it a certain amount of waste. For organic wastes, the intensity of pollution in the effluent is commonly expressed in terms of Biological Oxygen Demand, or BOD. Ultimate BOD is the amount of oxygen, in milligrams, which the metabolizing micro-organisms require to completely break down the waste into harmless end-products.

An equivalent definition is in terms of Population Equivalent, or PE, the average amount of household wastes generated per capita per day, and which corresponds to 0.25 lbs., or 113 grams of oxygen requirement per day to achieve complete decomposition.

Clean water at 20°C contains approximately 10 mg/liter of dissolved oxygen. If a BOD load of n mg/liter is added to this clean water, the resulting dissolved oxygen (DO) will be 10-n mg/liter under steady-state conditions. For comparison:

- At dissolved oxygen levels of approximately 4 mg/liter, higher fish life begins to die out.
- At 1 mg/liter, all aerobic life ceases.
- Acceptable BOD levels in bodies of water containing organic effluents range from 0.1 to 5 mg/liter, depending upon application.

U.S. (AVERAGE) ULTIMATE BOD OF INDUSTRIAL WASTES

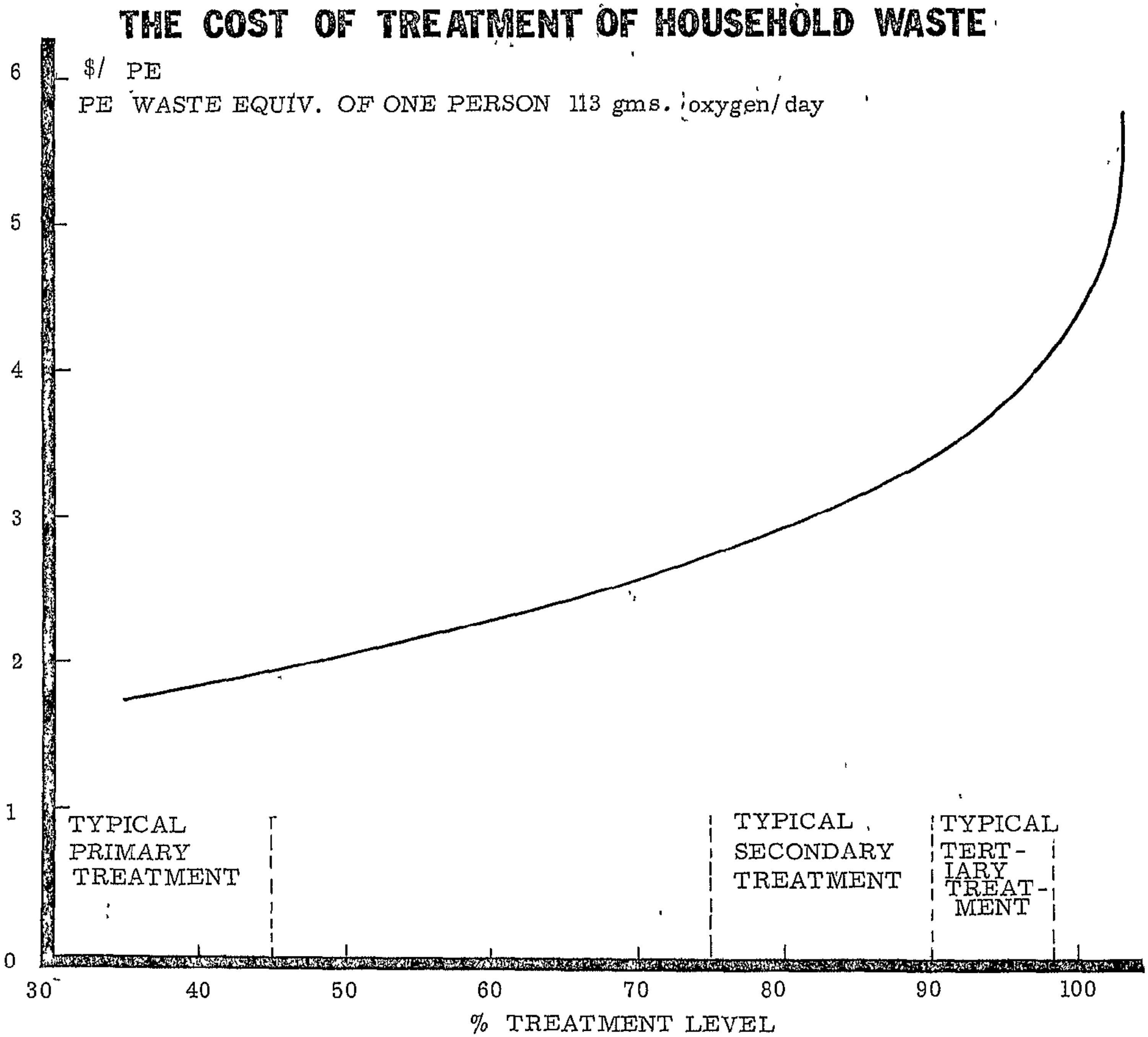


The cost of wastewater treatment increases with the degree of treatment.

"Percent treatment level" is defined as the percentage reduction in biological oxygen demand achieved within the effluent.

For example, U.S. urban sewer possesses a typical ultimate BOD of 500 mg/liter; 90% treatment would reduce this to 50 mg/liter.

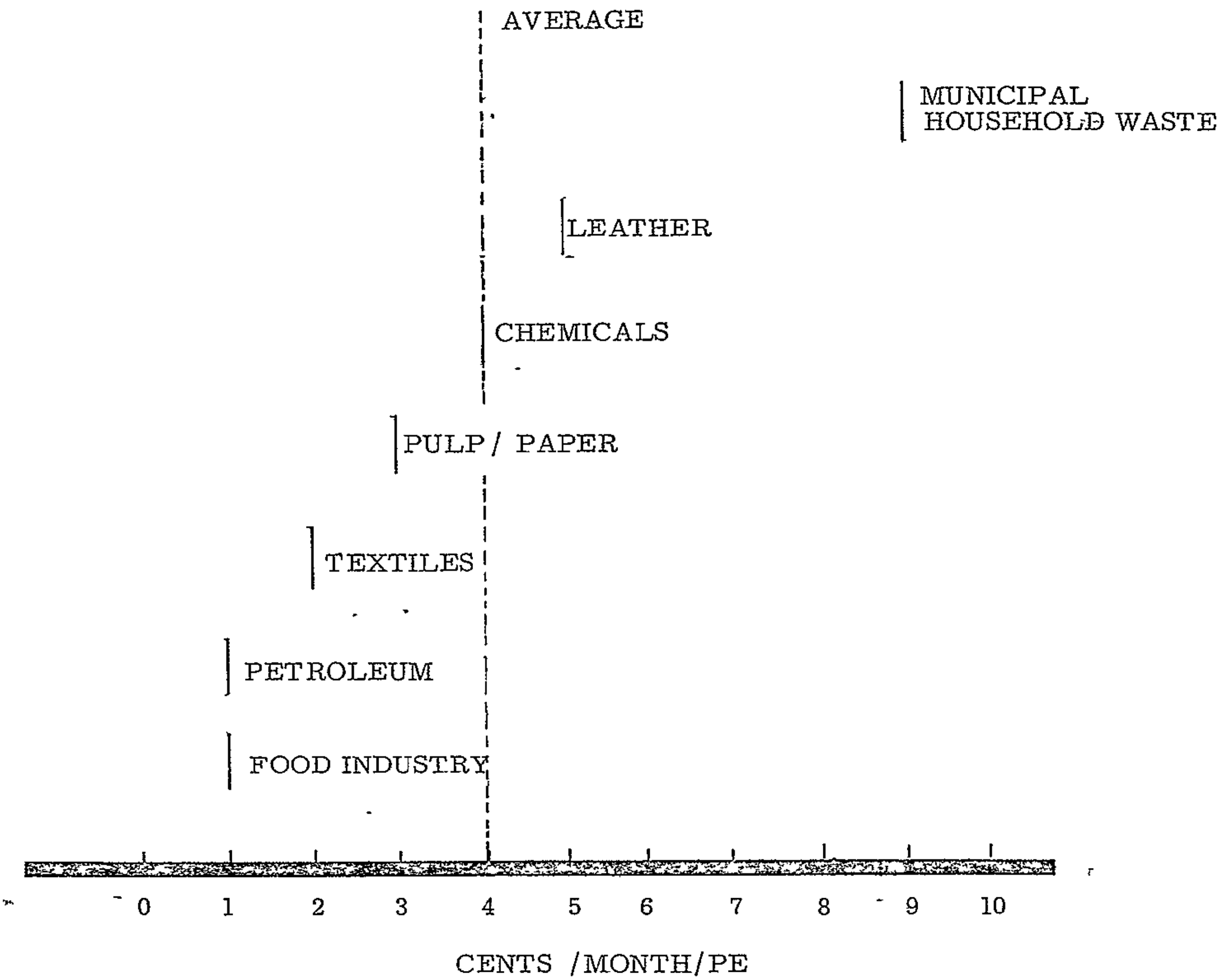
What this means is that the dilution required for treated waste is less than that for untreated. In the example cited, treated waste would require only 10:1 dilution to reduce the pollutant level to a tolerable 5 mg/liters, whereas untreated waste would require a dilution ratio of 100:1.


THE COST OF TREATMENT OF HOUSEHOLD WASTE
$/ PE
PE WASTE EQUIV. OF ONE PERSON 113 gms. oxygen/day
6
5
4
3
2
1
0
TYPICAL PRIMARY TREATMENT
TYPICAL SECONDARY TREATMENT
TYPICAL TERT-IARY TREAT-MENT
30
40
50
60
70
80
90
100
% TREATMENT LEVEL

The cost of treatment also varies with the type of waste,

AVERAGE WATER TREATMENT COSTS

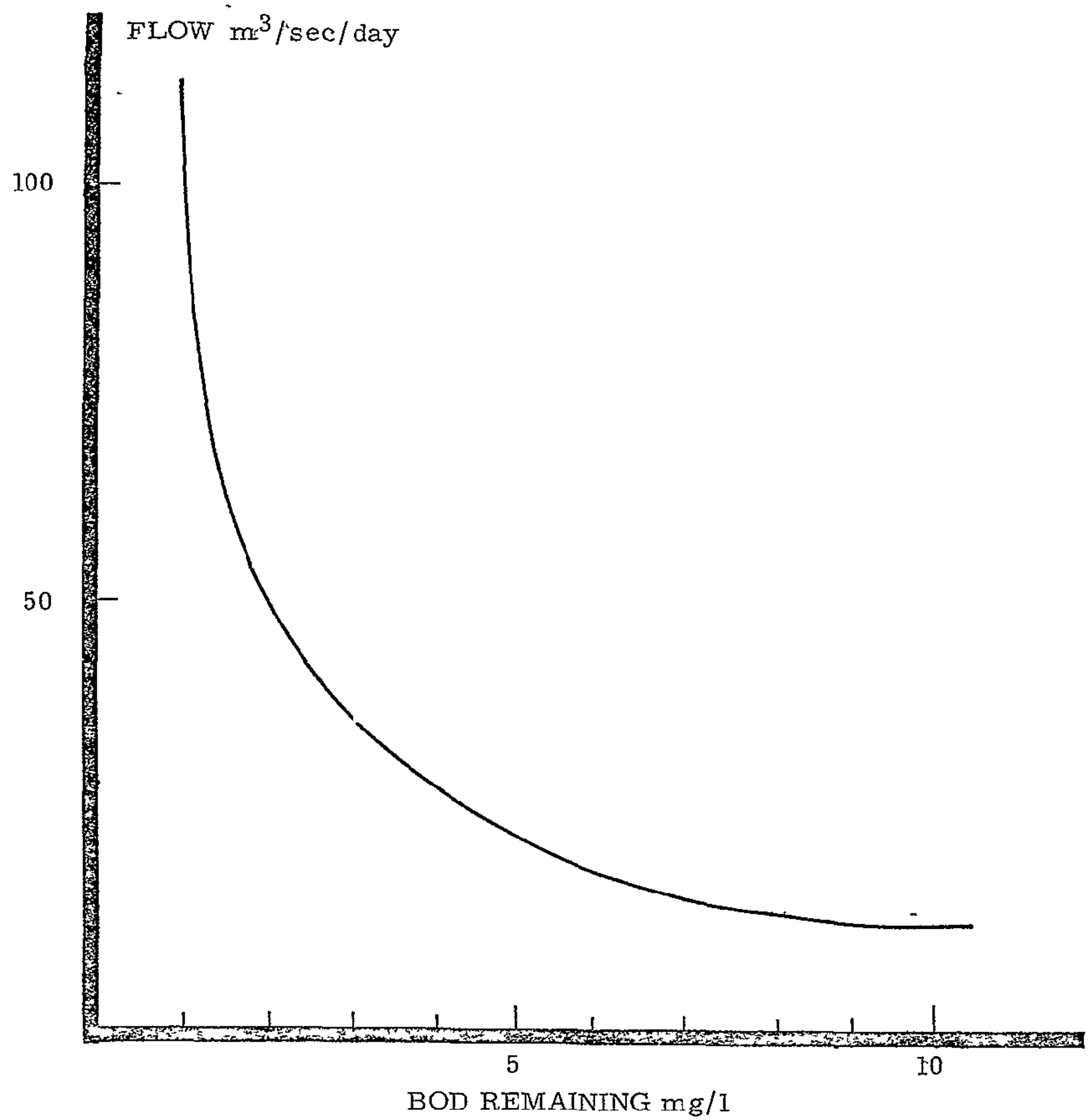
(80% TREATMENT)



An effect equivalent to treatment can be obtained by massive dilution. For example, if a sewer effluent with a BOD of 500 is diluted 10 times, an equivalent BOD of 50 mg/liter will result. To achieve tolerable pollution levels of 5 mg/liter, a dilution ratio of 100:1 is required.

To dilute 1 PE=113 grams of oxygen per day, to a level say of 5 mg/liter per day, requires a diluting amount of water equal to $\frac{113,000}{5}$, or 22.6 m^3. Since the average household effluent sewer is already 200 liters/person, the additional required dilution ratio is $\frac{22.6}{0.2}$, or 113:1.

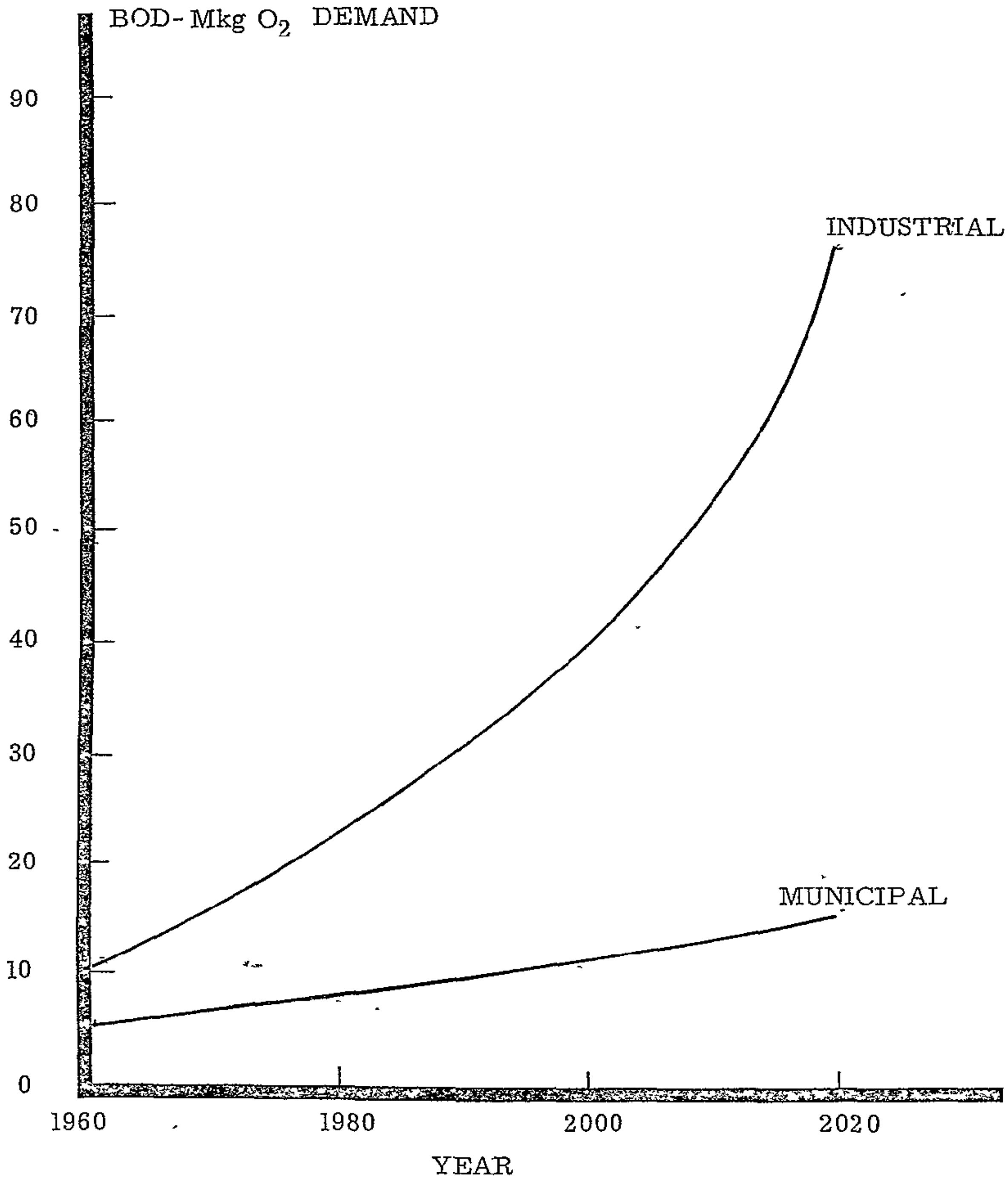
FLOW/PE TO ACHIEVE EQUIVALENT POLLUTION DEGRADATION



Choice of the optimum mix between treatment and dilution is economically very important due to the large, and ever-increasing, effluent PE level of the U.S. as a whole.

The problem is under active consideration by the Environmental Protection Agency.

TOTAL YEARLY BOD PRODUCED IN THE U.S.



63

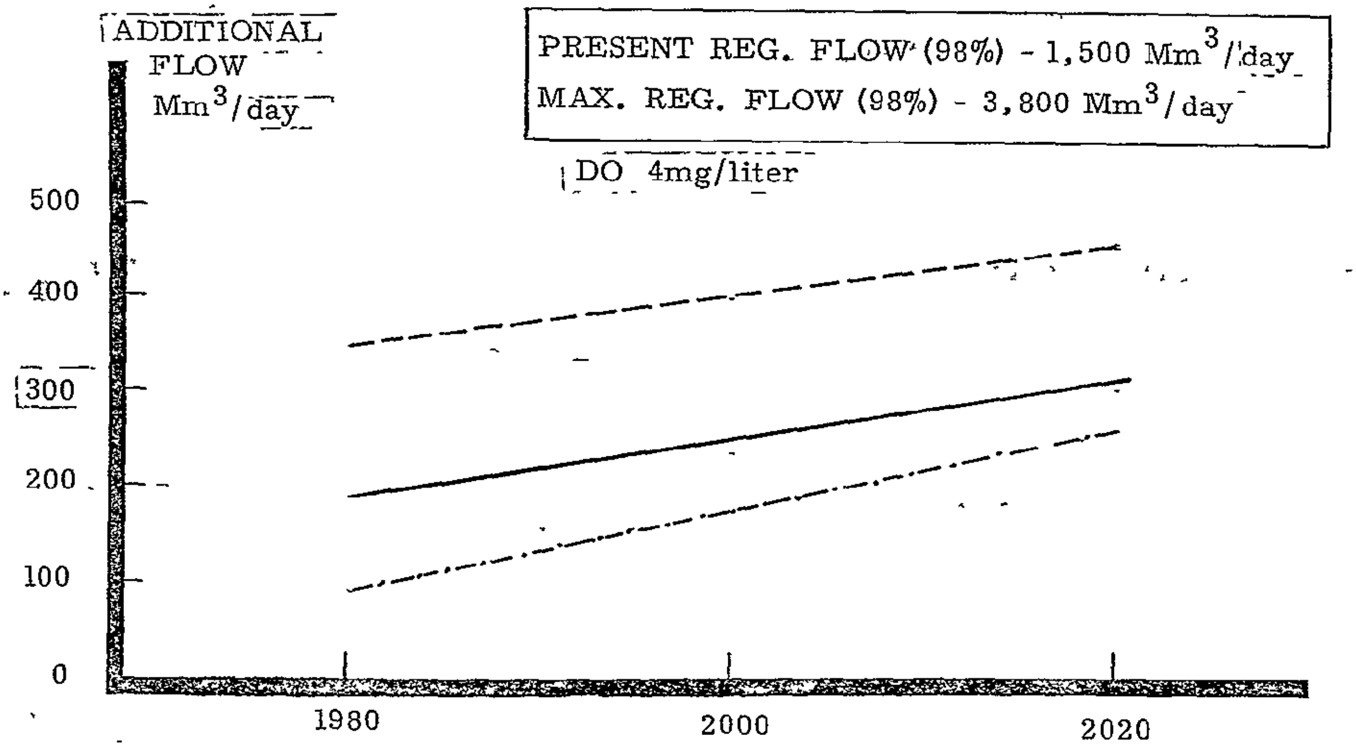
One extreme of the mix is the "all treatment" approach. The other is the "all dilution" approach.

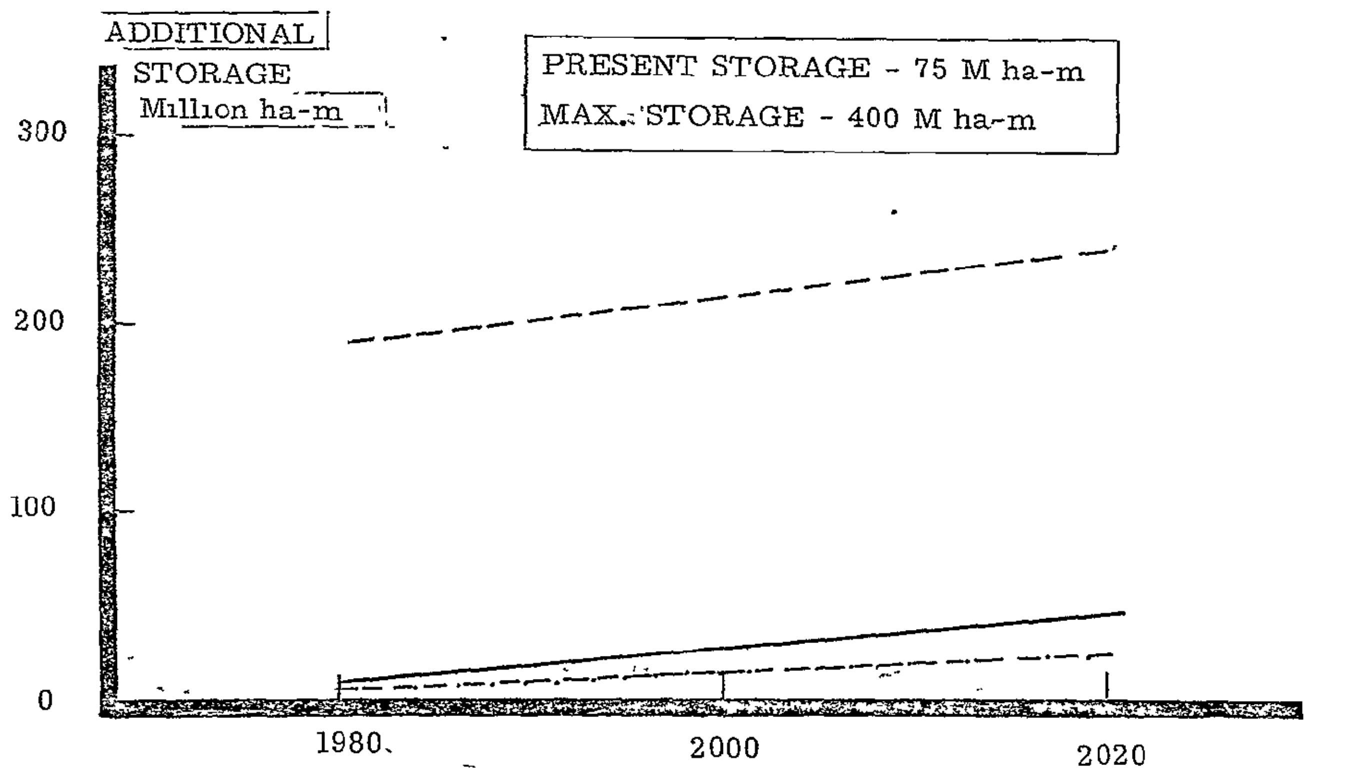
Neither extreme is optimal; there is an in-between mix which possesses the lowest cost.

The impact of each policy upon additional storage and flow requirements, averaged over the U.S. and based upon a (barely) tolerable resulting DO level in watercourses of 4 mg/liter, is shown opposite.

Note that the "all dilution" approach would require quadrupling the existing reservoir capacity.

PHYSICAL IMPACT OF POLLUTION ABATEMENT POLICIES





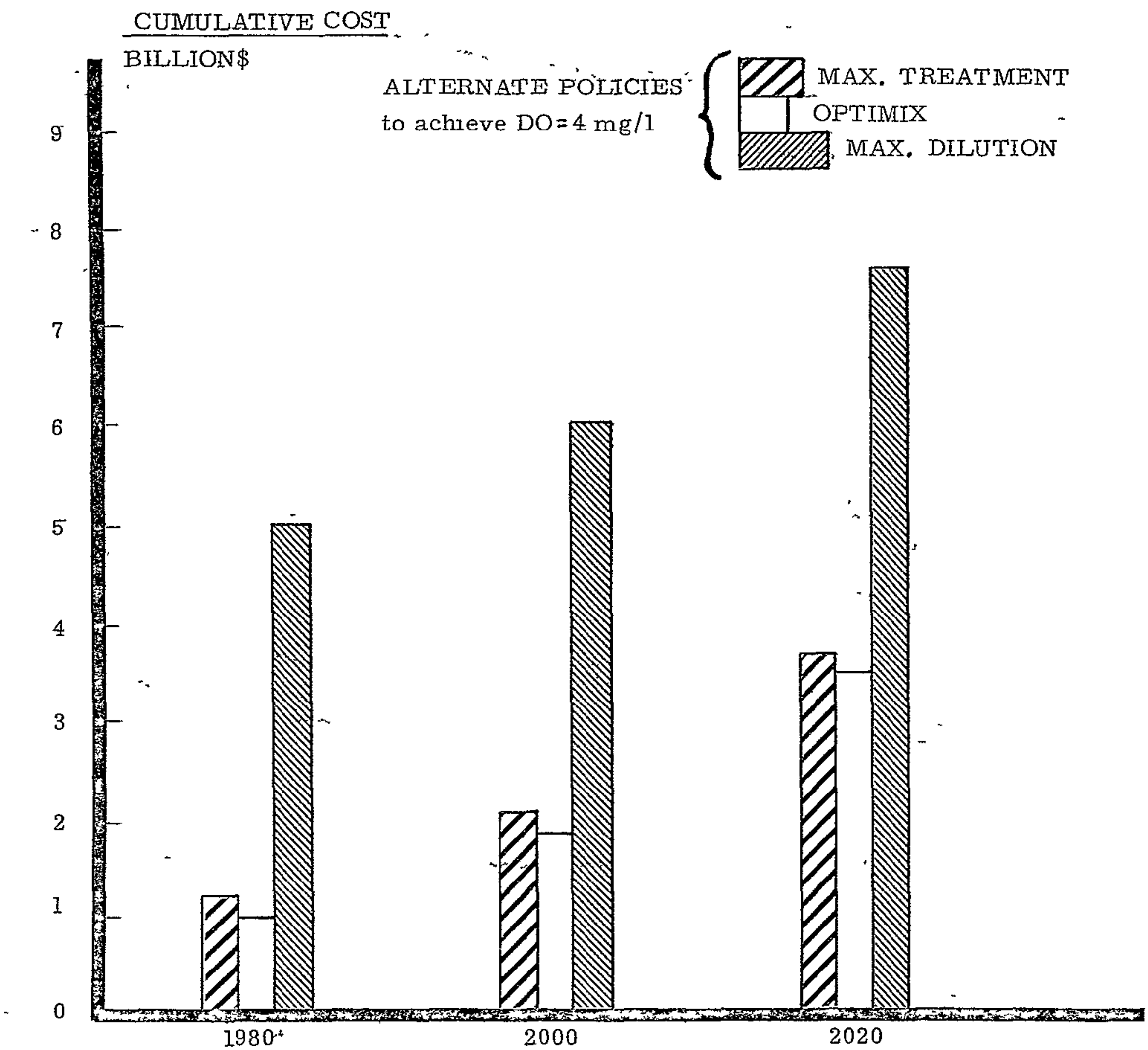
---- DILUTION

—— OPTIMIX

The costs of each policy for the entire U.S. indicate that the "all dilution" approach is by far the most expensive. The optimum mix would require a 20% increase in reservoir development by AD 2000.

This applies to a (barely) tolerable resulting DO level of 4 mg/liter in most U.S. watercourses.

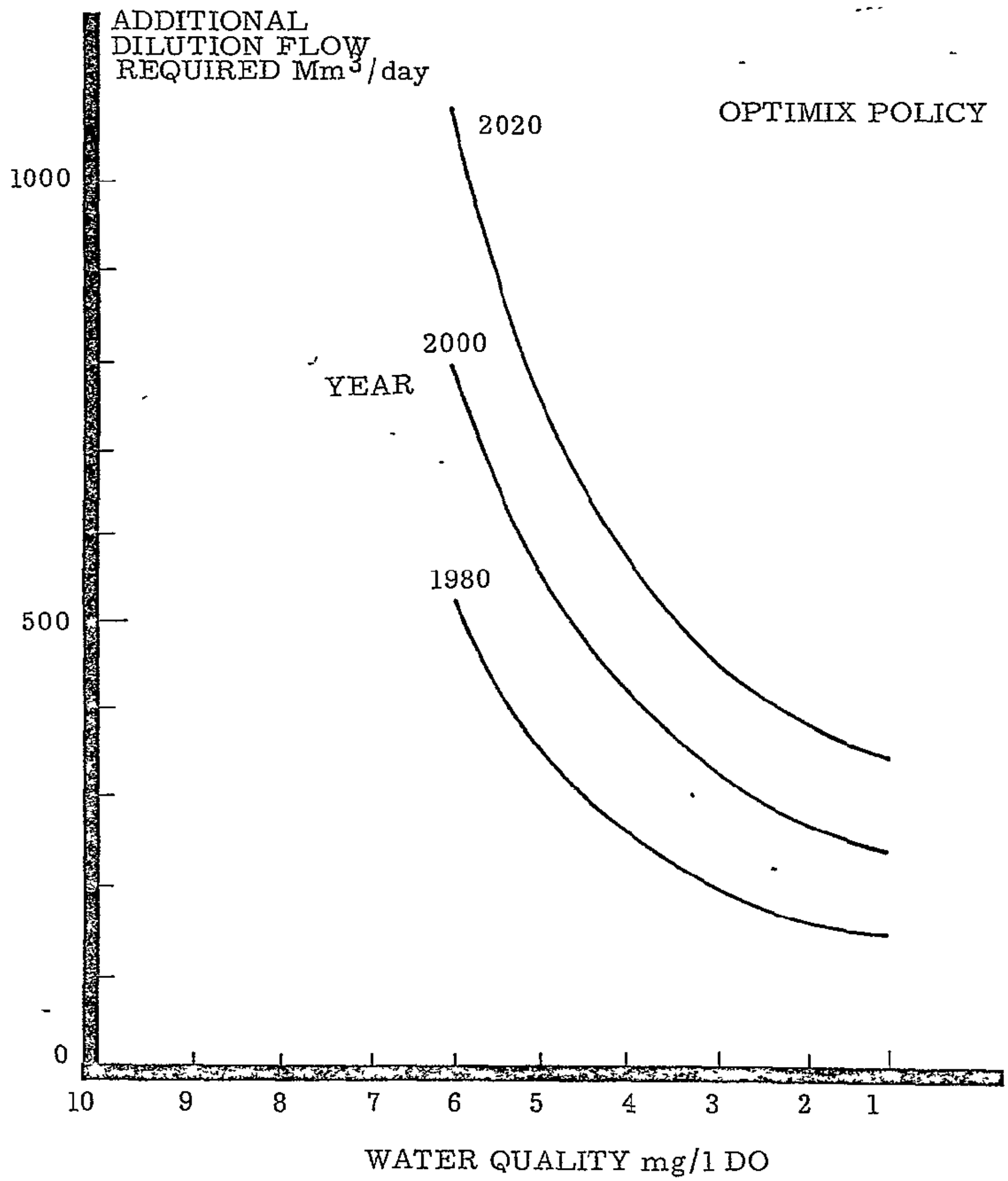
ECONOMICS OF POLLUTION ABATEMENT



To achieve higher DO levels, and thus cleaner water-courses, the flow requirements (and corresponding reservoir development levels and costs) increase drastically. Although the final policy decision by EPA is still unknown, the point is that pollution dilution is likely to become a major new factor in water demand.

The key economic "driver" is reservoir development.

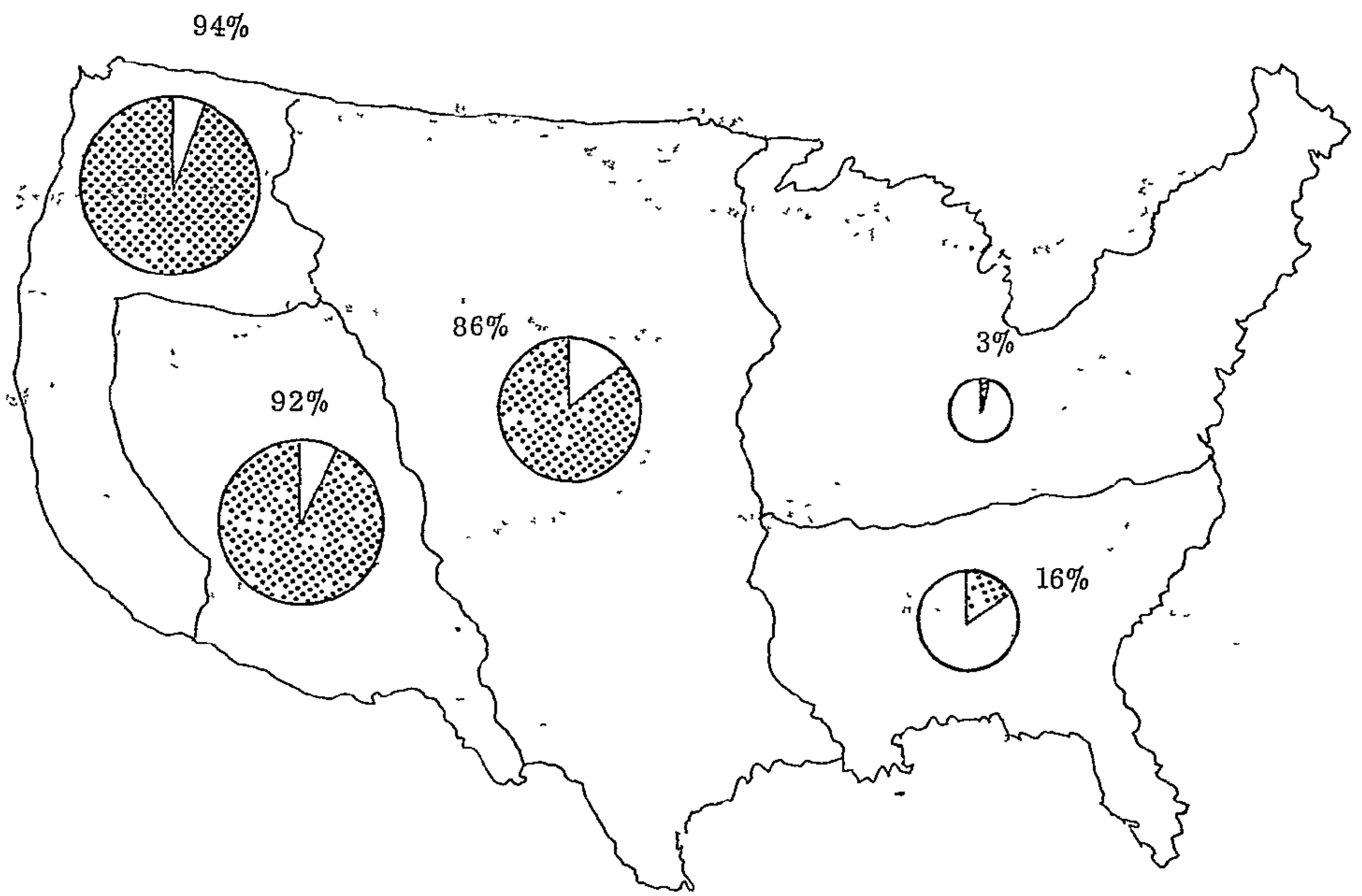
EFFECT OF ALTERNATE WATER QUALITY POLICIES ON REQUIRED FLOW



3.6 WATER REQUIREMENTS FOR IRRIGATION

Agricultural irrigation is at present the major consumer of water in the arid Western regions.

IRRIGATION WITHDRAWALS AS A PER CENT OF TOTAL WITHDRAWALS 1970

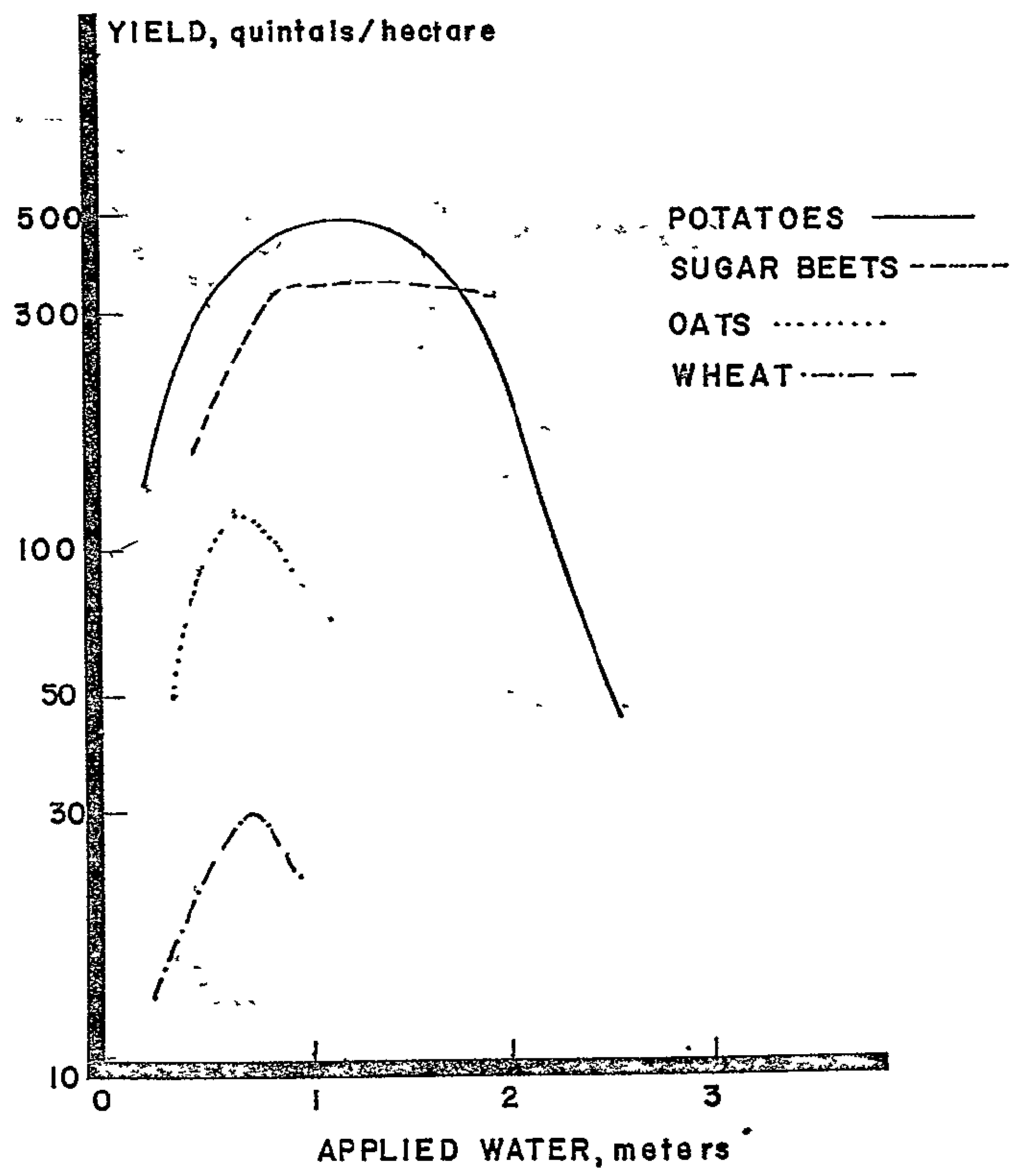


	Mm^3/day
NORTH PACIFIC	212.84
SOUTHWEST	160.58
MID-CONTINENT	154.24
SOUTHEAST	16.67
NORTHEAST	9.98

Irrigation water is needed to supplement deficiencies in precipitation water. The effect of too much water can be as deleterious as that of insufficient water.

It should be noted that yield-versus-applied water relationships vary significantly as a function of the type of crop, soil characteristics, and climate.

EXAMPLES OF CROP YIELD AS A FUNCTION OF APPLIED WATER

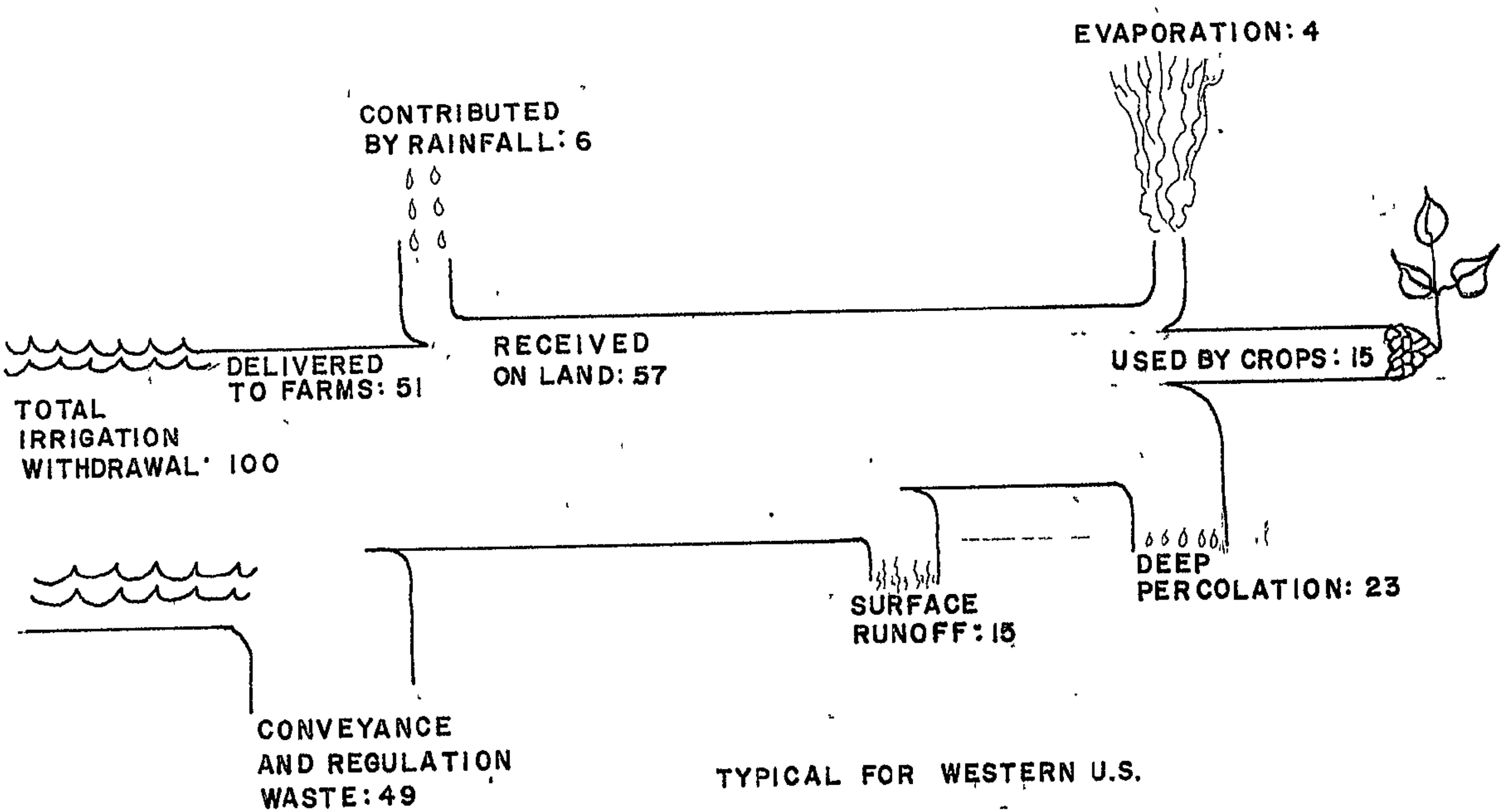


Irrigation water is generally characterized by heavy conveyance losses.

On the average, approximately half of the withdrawn water reaches the irrigation site.

Approximately 70% of this water is lost through surface runoff, percolation into the ground, and evaporation: thus, typically only 15% of the withdrawn water reaches and is used by the crops.

There exists thus a significant "leverage" between water used by crops and total withdrawal: relatively small changes in crop water can cause notable variations in the quantity of total irrigation water withdrawal.



DISPOSAL OF IRRIGATION WATER IN PERCENT OF THE TOTAL WITHDRAWAL

How is the water used by crops?

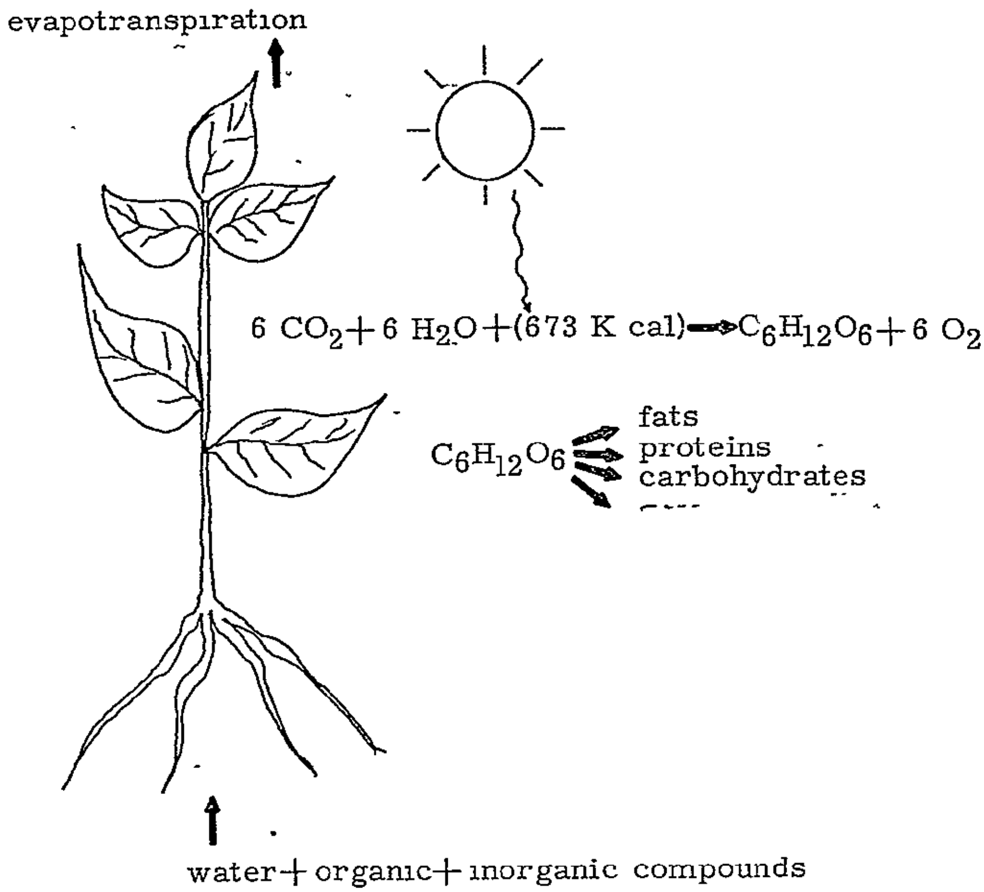
Plants Require water for three basic purposes:

- To live, i.e., to metabolize the atmospheric CO_2 and turn it into plant tissue.
- To grow, i.e., to add plant tissue.
- To cool the plant.

The principal metabolic reaction, photosynthesis within the leaf, occurs between atmospheric CO_2 and water. In addition, water, carrying trace nutrients, must circulate upwards from roots to leaves.

A certain amount of evapotranspiration is necessary to generate the pressure differential needed to circulate water from roots to leaves.

The excess is used up for cooling purposes.

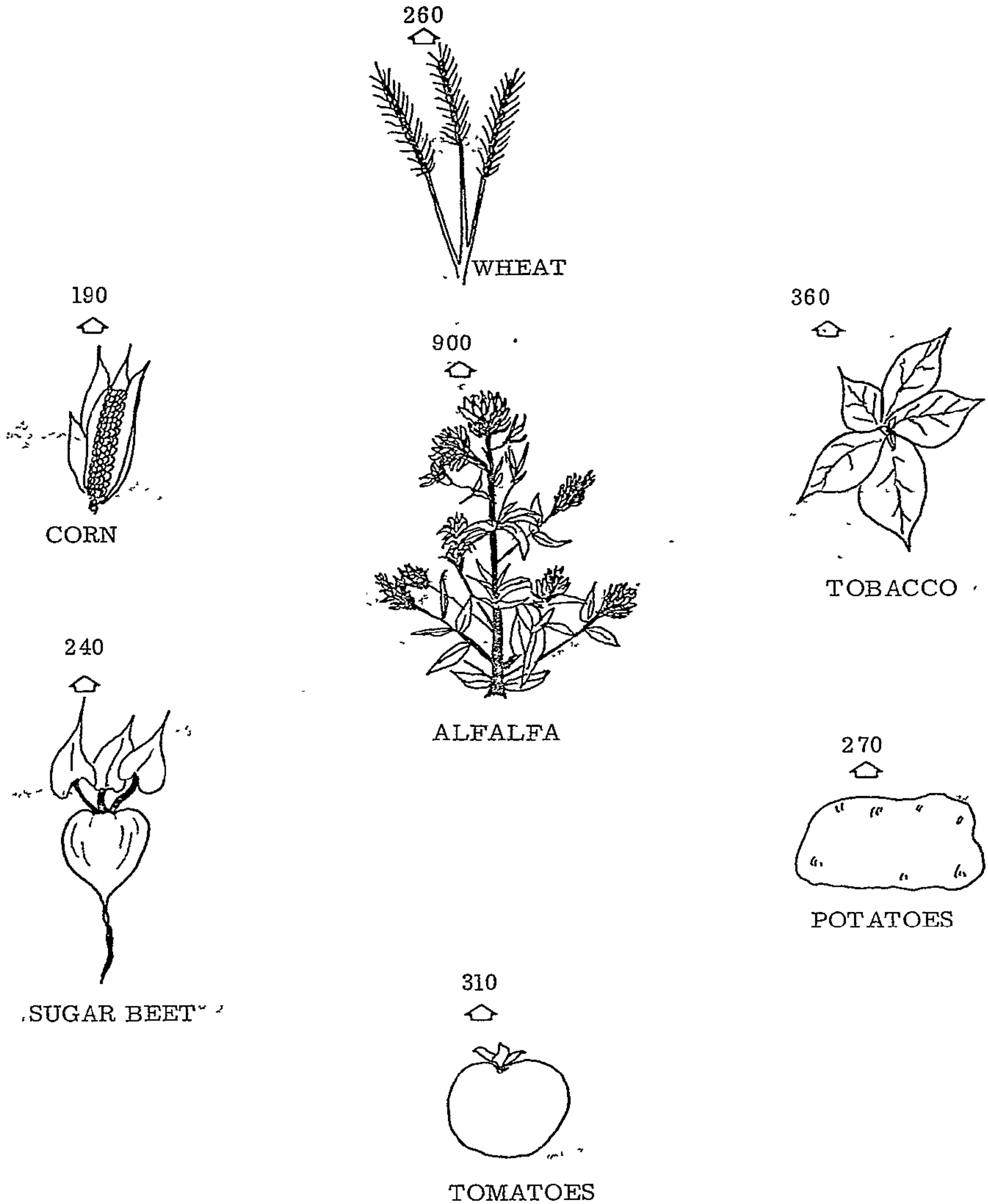


WATER REQUIREMENT: 10 to 20 grams/gram of ultimate plant dry weight over growing season.

BASIC METABOLIC AND GROWTH PROCESS OF PLANTS

By far the largest amount of water used by plants is for evapotranspiration, which can reach as much as 98% of the total water absorbed by the plant.

The figures shown opposite are typical· they vary significantly with soil type, climate and amount of irrigation water.



TOTAL WATER USED BY CROPS FOR EVAPOTRANSPIRATION

During growing season; in grams per gram of dry plant weight

Evapotranspiration is driven by the difference in relative humidity between plant leaf and air, and by the soil humidity, since if the soil humidity is too low, water cannot be drawn by the plant.

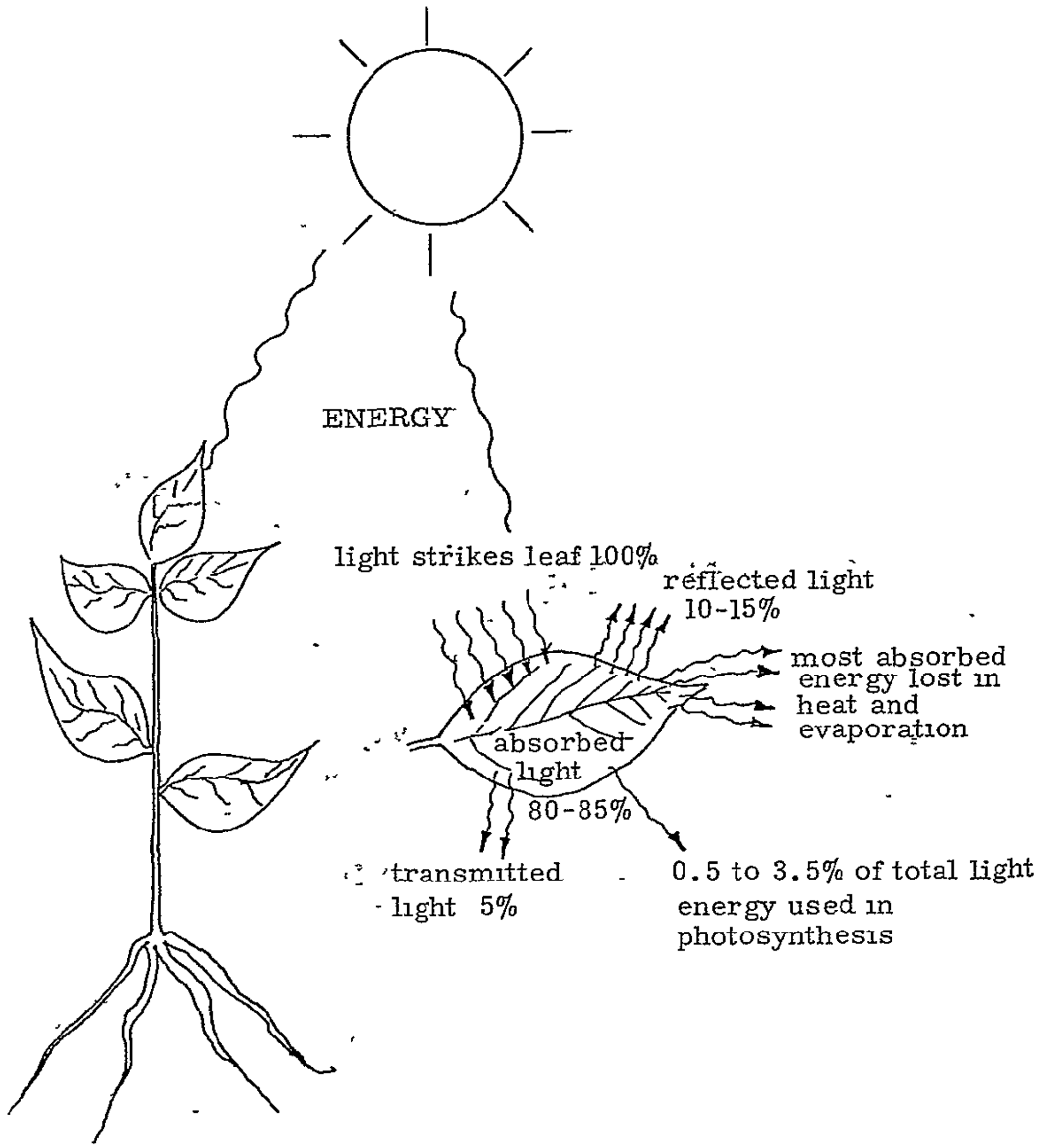
Uncertainty exists among investigators as to whether plant growth and evapotranspiration are significantly affected by soil humidities above the wilting point.

The input phenomena which affect the leaf-air relative humidity are:

- Solar Radiation - its absorption by the leaf raises leaf temperature and corresponding vapor pressure.
- Atmospheric Temperature - increases evapotranspiration by 20 to 30 percent per $10^{o}C$.
- Wind Speed - which carries vapor away, causing increased plant transpiration. Some investigators indicate that a 5 mph wind increases transpiration 20%, 10 mph 35%, 15 mph 50%.

Considerable uncertainty exists among investigators as to the exact relationships between driver phenomena and the actual quantities of water evapotranspirated.

EVAPOTRANSPIRATION DRIVERS



DRIVER 1: RELATIVE HUMIDITY DIFFERENCE BETWEEN LEAF AND AIR - "ACQUEUS VAPOR PRESSURE DEFICIT OF AIR"

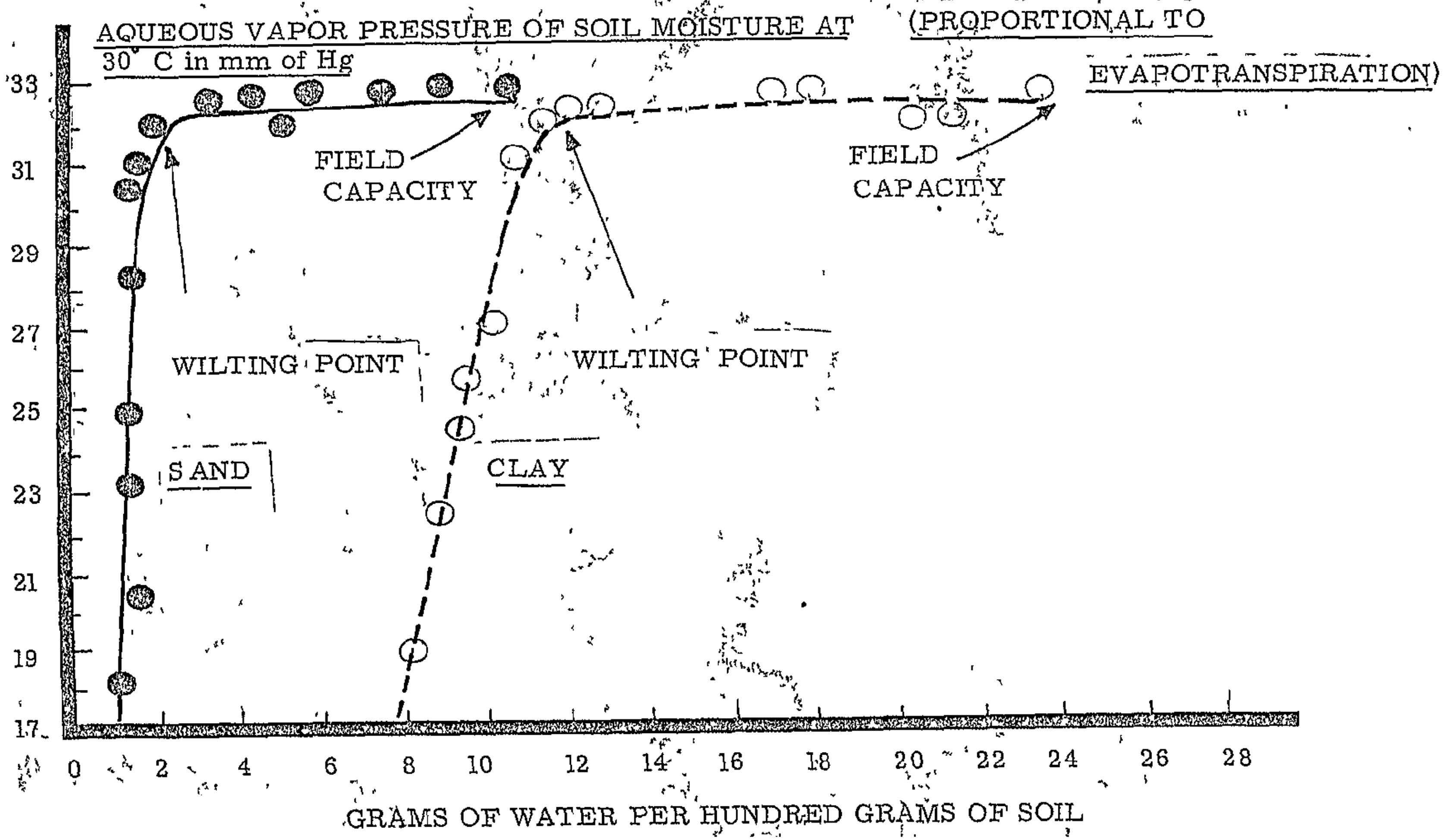
DRIVER 2: SOIL MOISTURE

DRIVING PHENOMENA: SOLAR RADIATION
TEMPERATURE
WIND

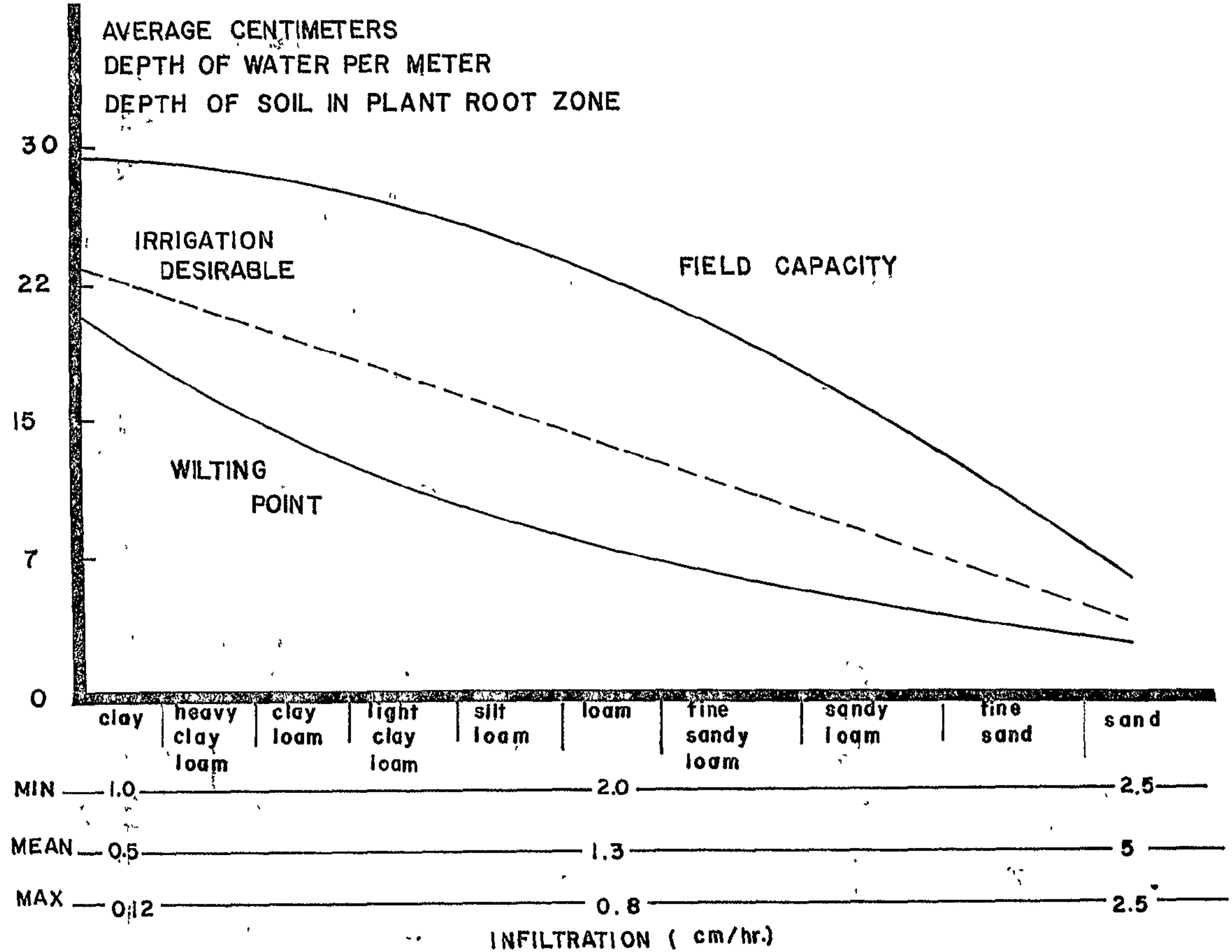
For example, some researchers report that evapotranspiration is essentially constant, above the wilting point, for any given ambient temperature.

The wilting point is the soil's water content, below which the plant is unable to maintain turgor: it varies as a function of soil type because different soils have different resistances to water extraction by plants.

EXPERIMENTALLY OBSERVED BEHAVIOR OF PLANT EVAPOTRANSPIRATION



For this reason, several investigators recommend that the total water supplied to crops be such as to maintain soil humidity above, but close to, the wilting point.


AVERAGE CENTIMETERS
DEPTH OF WATER PER METER
DEPTH OF SOIL IN PLANT ROOT ZONE
30
22
15
7
0
IRRIGATION DESIRABLE
FIELD CAPACITY
WILTING POINT
clay
heavy clay loam
clay loam
light clay loam
silt loam
loam
fine sandy loam
sandy loam
fine sand
sand
MIN 1.0 2.0 2.5
MEAN 0.5 1.3 5
MAX 0.12 0.8 2.5
INFILTRATION (cm/hr.)

Considerable discrepancies exist among empirical evapotranspiration models.

Shown opposite are the predictions, for the same geographical area and the same crop, among the better known and most employed evapotranspiration formulations.

In view of the importance of water usage by agriculture, which occurs mostly within regions where the marginal cost of water is high, and of its high content of surface observables, the application of remote sensing to the optimization of irrigation policies and practices can provide significant improvements.

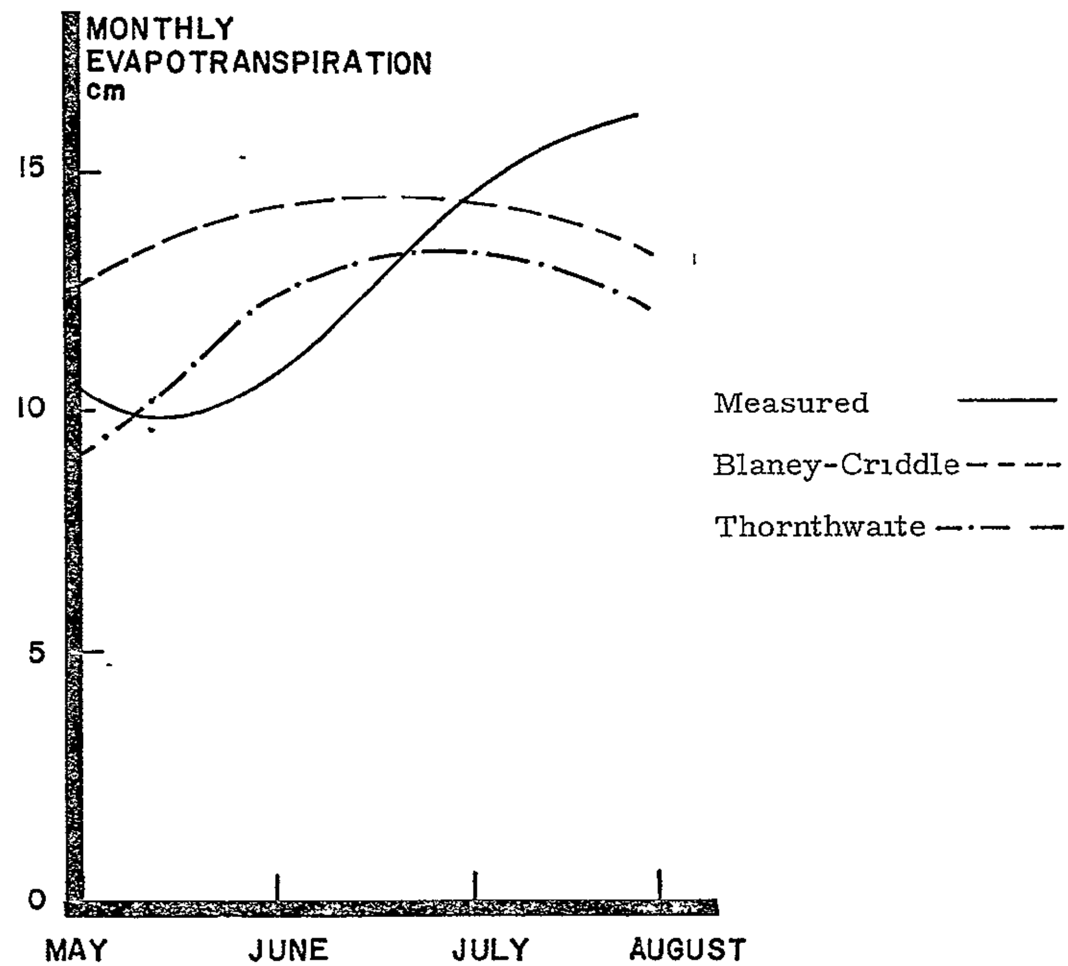
Important investigations are:

1. Assessment of what constitutes optimal crop water requirements. Much of this task can probably be performed by improved correlation of existing data.
2. Determination of evapotranspiration models which best fit the conditions of each specific region.
3. Quantification of the observables which are best amenable to direct or indirect remotely sensed observations. Typically: insolation, crop spectral reflectance indicative of plant turgor, and eventually, as improved sensing means become available, atmospheric humidity and temperature.

A major portion of the above investigations can be performed by improved correlation of existing regional data.

TYPICAL ERRORS OF PRINCIPAL EVAPOTRANSPIRATION FORMULATIONS

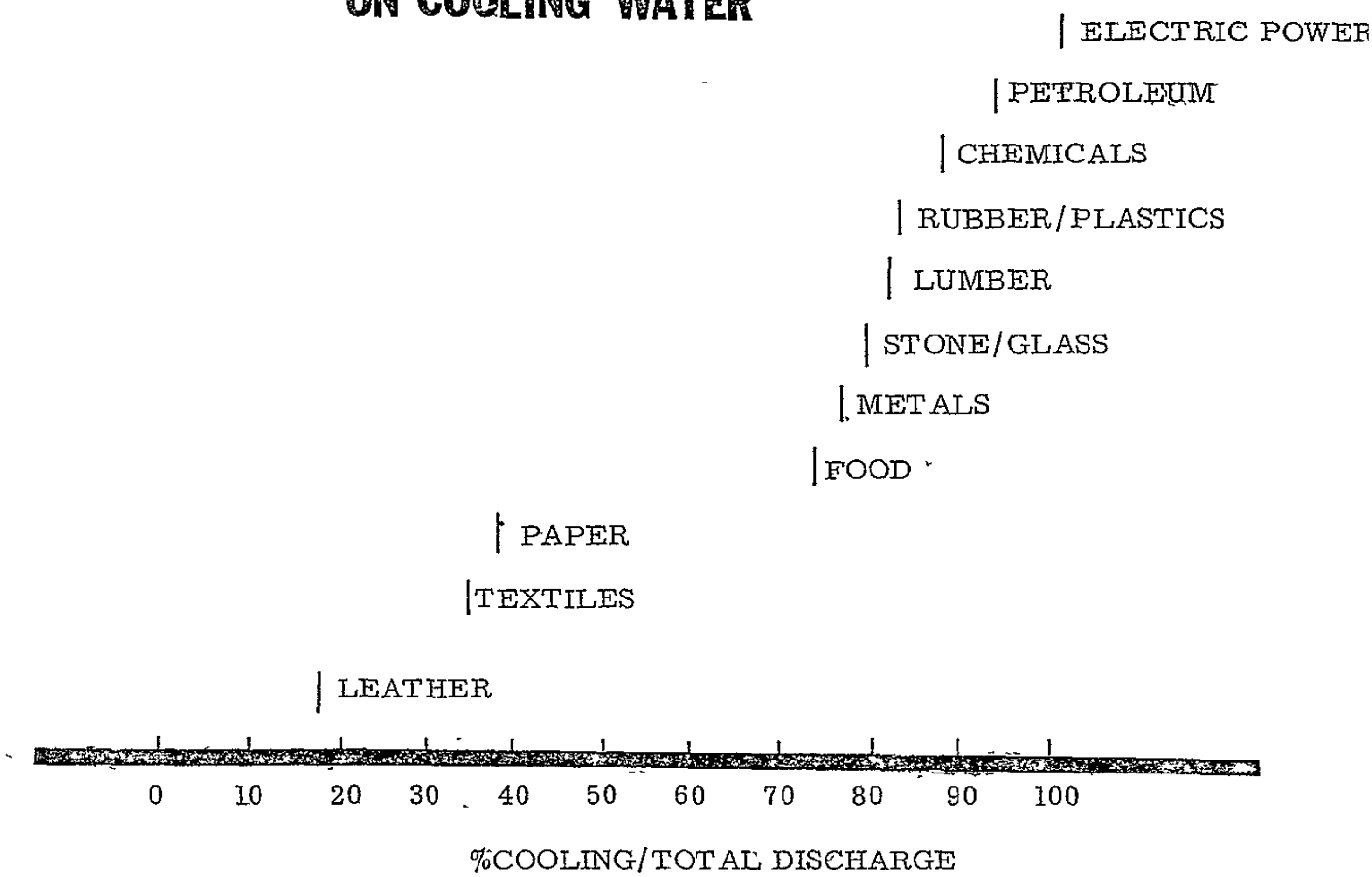
Alfalfa, San Joaquin Valley
average of 2 years



3.7 WATER REQUIREMENTS FOR INDUSTRIAL COOLING

A significant fraction of industrial water usage is devoted to cooling industrial processes.

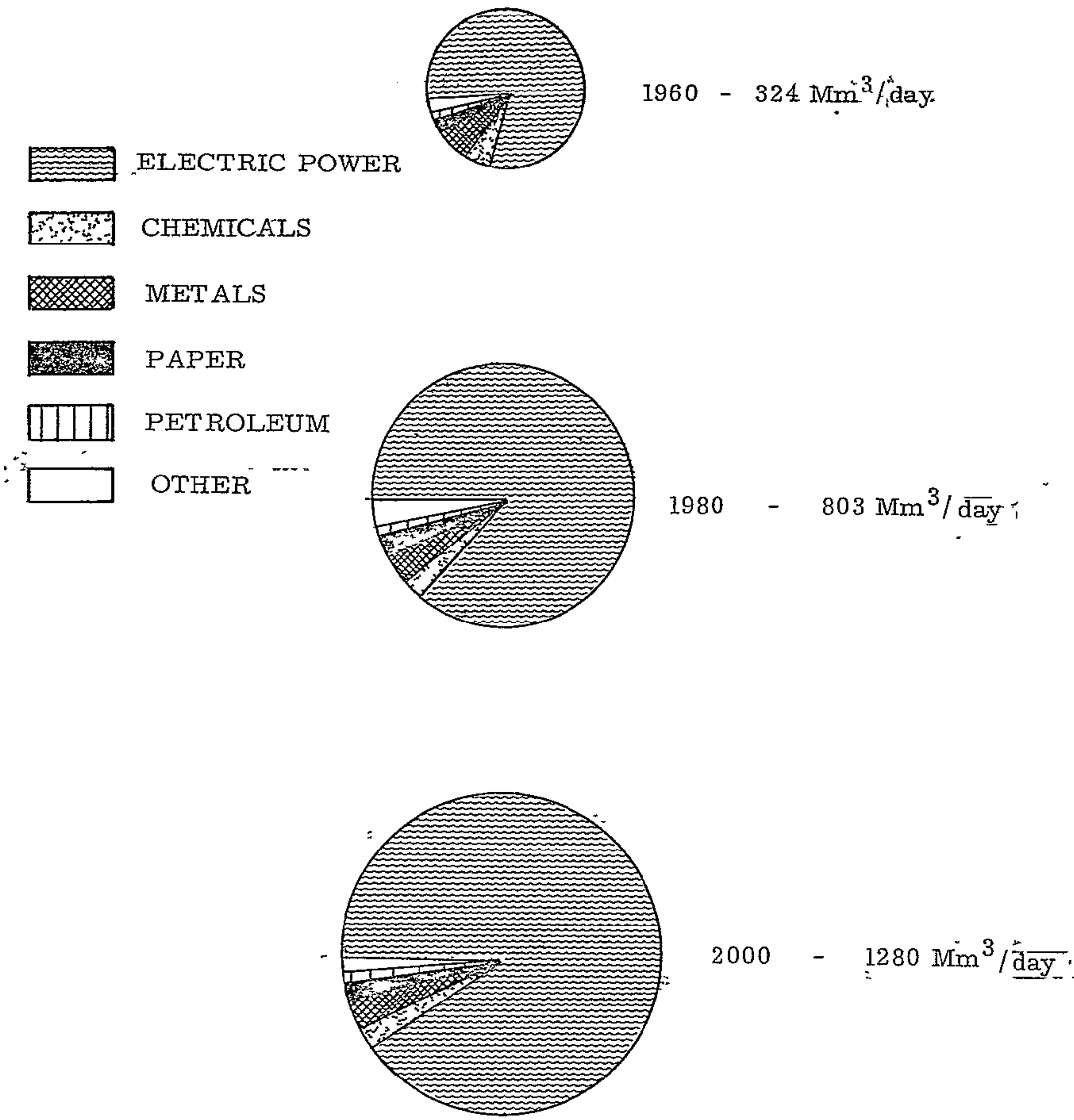
AVERAGE INDUSTRIAL DEPENDENCE ON COOLING WATER



In absolute values, the overwhelming user of cooling water is the electrical energy generating industry.

Cooling is needed regardless of the primary fuel employed. In the case of nuclear fuel, the efficiency is somewhat less than for fossil fuel. Approximately 20% more cooling water per kilowatt hour generated is required in nuclear installations with respect to fossil fuel fired plants.

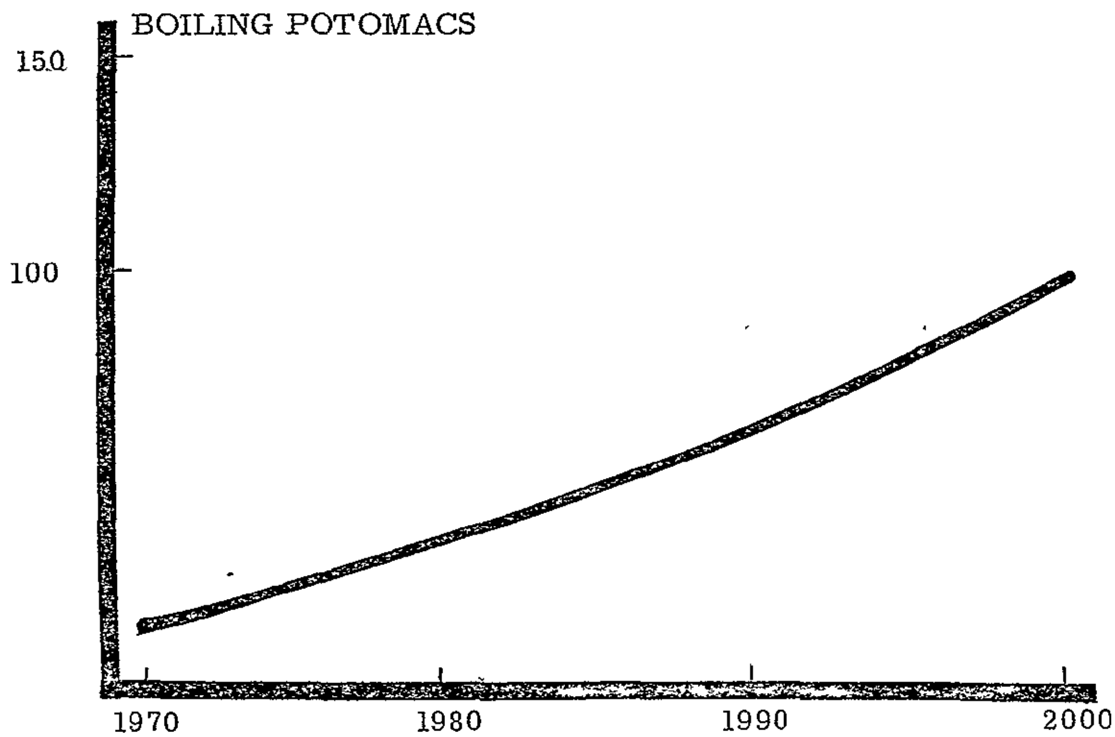
GROWTH OF INDUSTRIAL COOLING IN THE U.S.



A compact way to look at the electrical energy cooling requirements is to describe the required cooling in terms of Boiling Potomacs. This is the heat quantity required to bring River Potomac (flow of 1 billion gals/day) from normal temperature ($20^{o}C$) to the boiling point ($100^{o}C$).

By comparison, note that the present total U. S. 98% regulated flow is equivalent to 375 Potomacs.

COOLING REQUIREMENTS OF ELECTRICAL ENERGY GENERATION

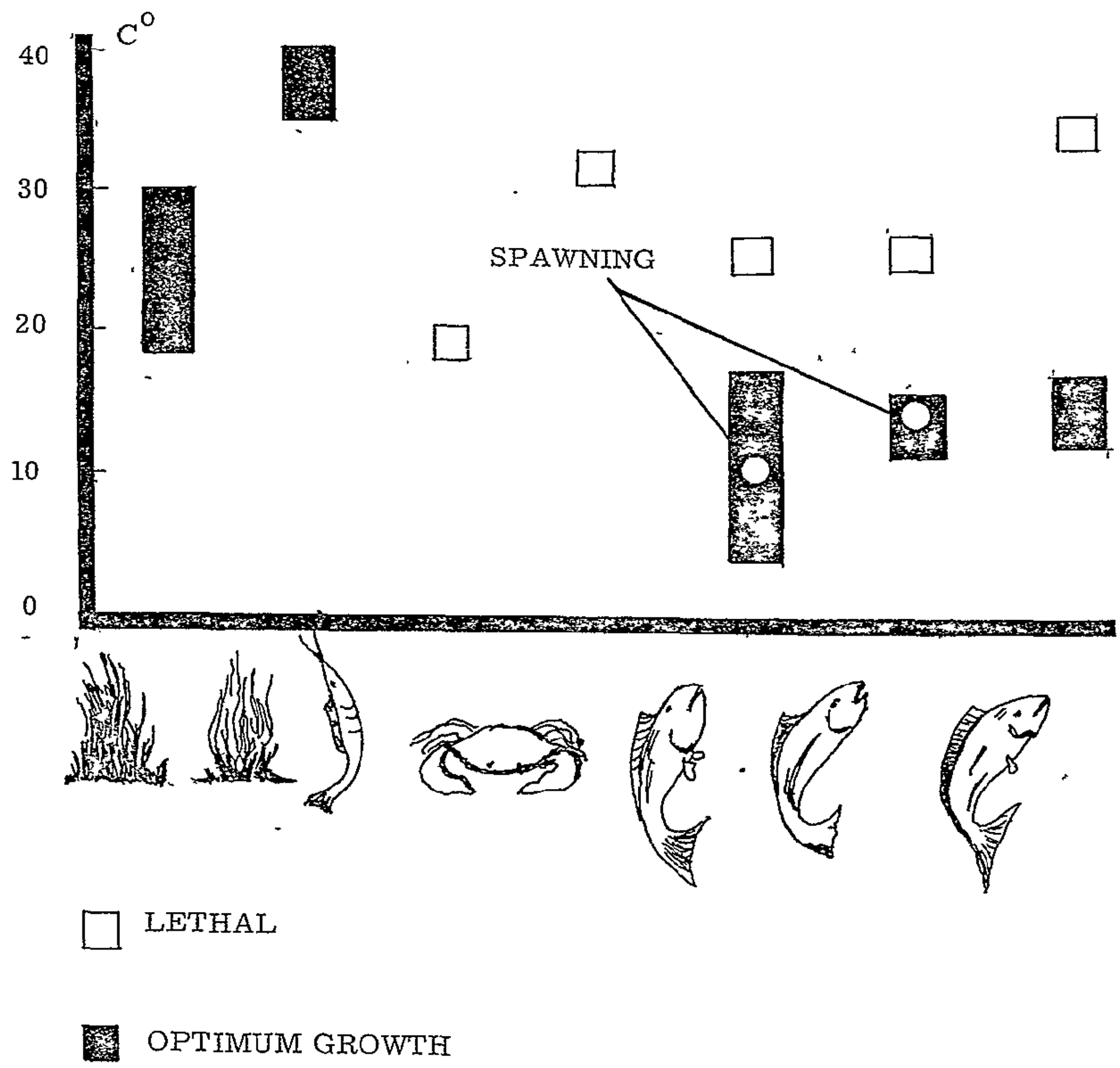


In practice, dumping of treated water is severely restricted by law.

The reason is its estimated effect on aquatic life. Fish thrive best within a limited temperature range. A prolonged temperature rise much above the range of each species will cause death. The problem is not so much the killing of adult fish, since they can escape towards cooler waters; rather, the fact that temperatures well within the adult's tolerance are lethal to larvae, thus inducing extinction of the species within the warmed waters.

The other problem is that higher temperatures favor growth of acquatic plants, which consume oxygen, thus imposing additional environmental stress upon fish.

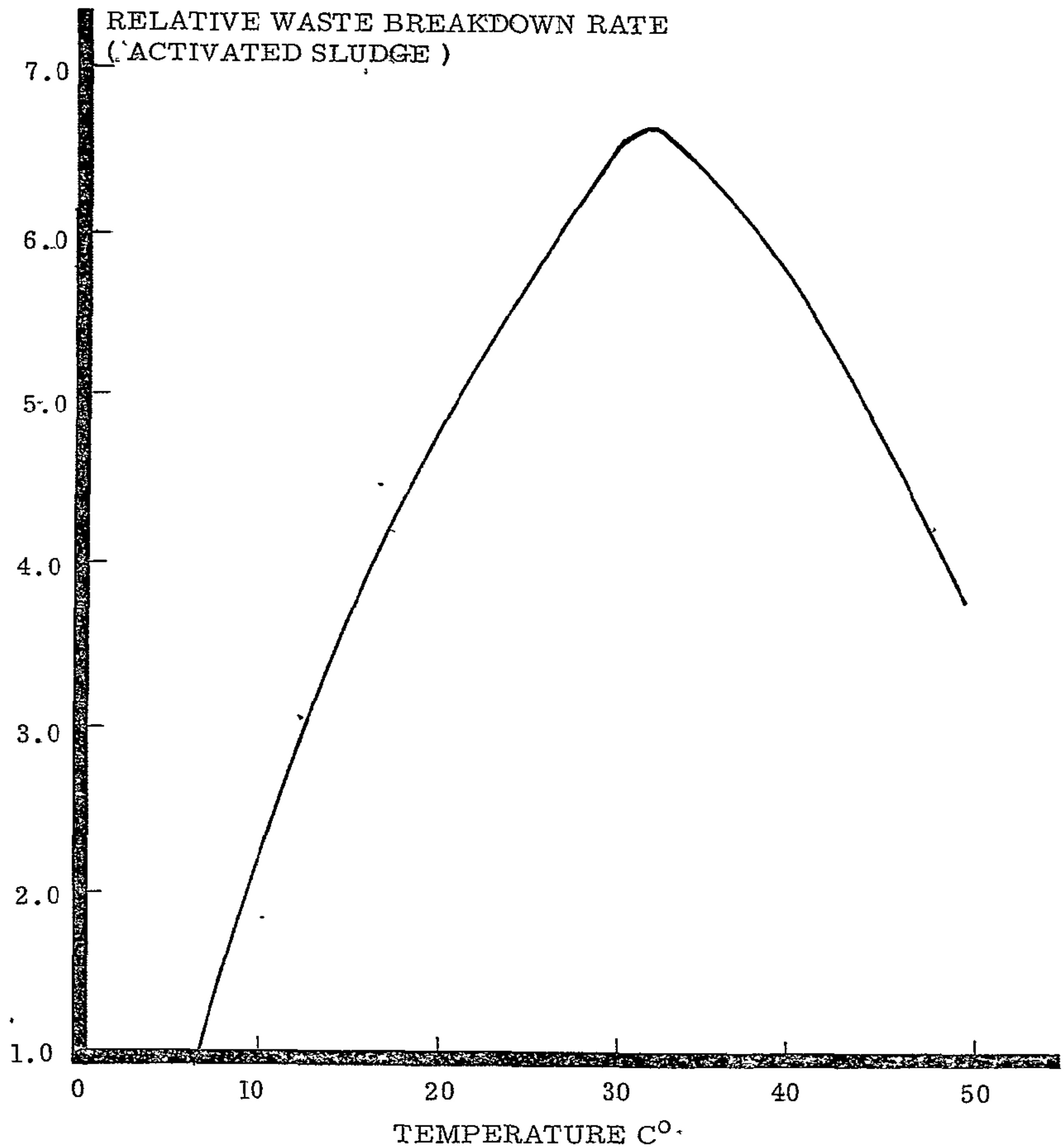
THE EFFECT OF TEMPERATURE ON FISH AND IMPORTANT MARINE FLORA



By contrast, higher temperatures favor bacterial action, which aids the digestion of pollutants.

Although evidence for widespread damage and deleterious modifications in the ecological balance from heated waters is not conclusive, Federal law now restricts the temperature differential between heated effluent and river to $5^{o}C$ in Summer, $10^{o}C$ in Winter, and limits maximum outlet temperature to $32^{o}C$.

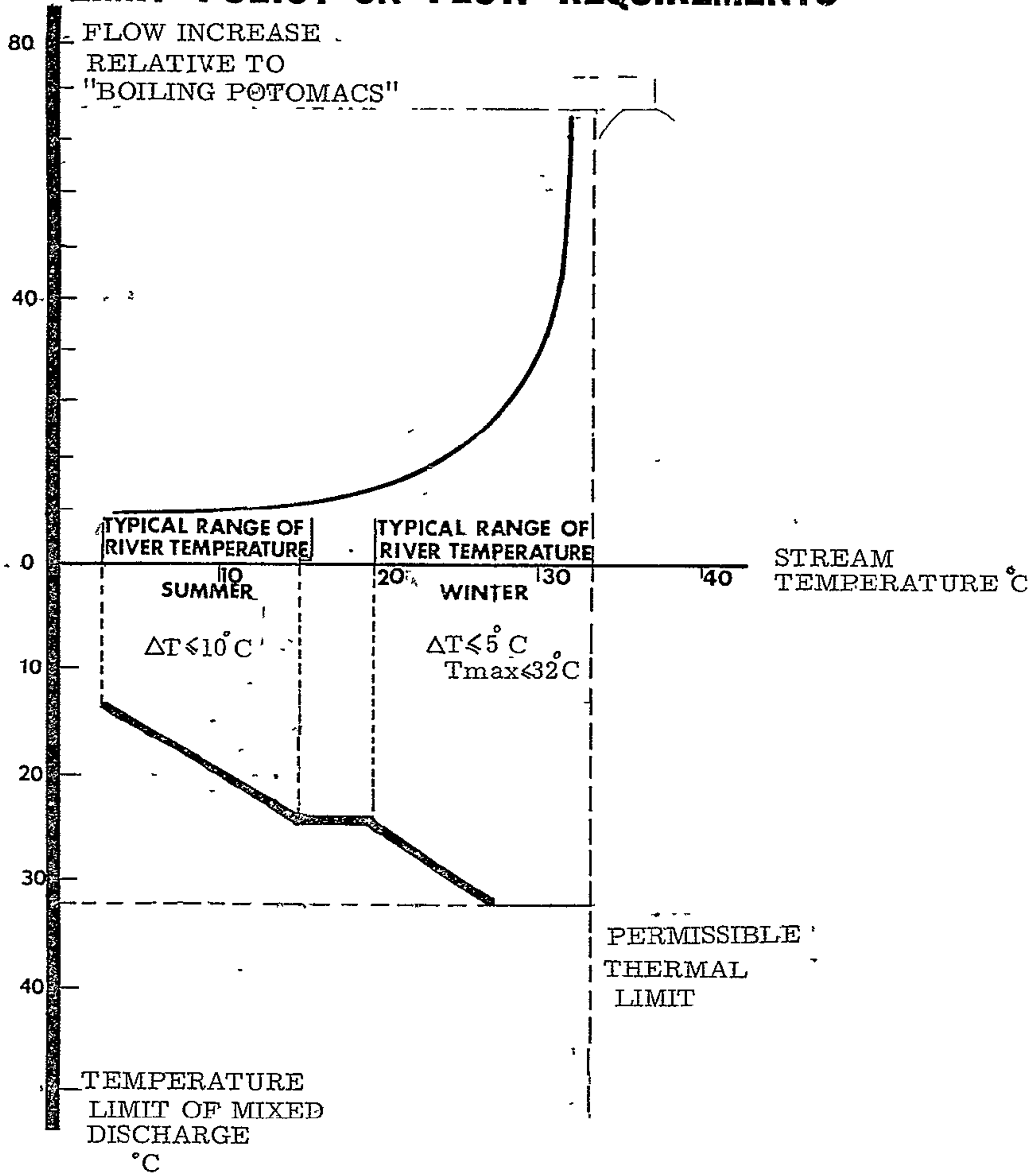
THE EFFECT OF TEMPERATURE ON BACTERIA



These restrictions vastly increase the required cooling water flow.

For example, the 10° (Winter) temperature restriction increases the required flow 8 times over and above that of Boiling Potomacs. The $5^{\circ}C$ (Summer restriction) causes a sixteen-fold flow increase. As the $32^{\circ}C$ upper limit is approached, flow requirements increase even further.

THE EFFECT OF THERMAL COOLING LIMIT POLICY ON FLOW REQUIREMENTS



A feel for the magnitudes involved can be obtained by looking at the practical situation forecasted for the River Potomac.

Present plans by Potomac Electric Company for constructing a fossil-fuel fired electric generating plant on the Potomac require the worst-condition (Summer) flows shown opposite.

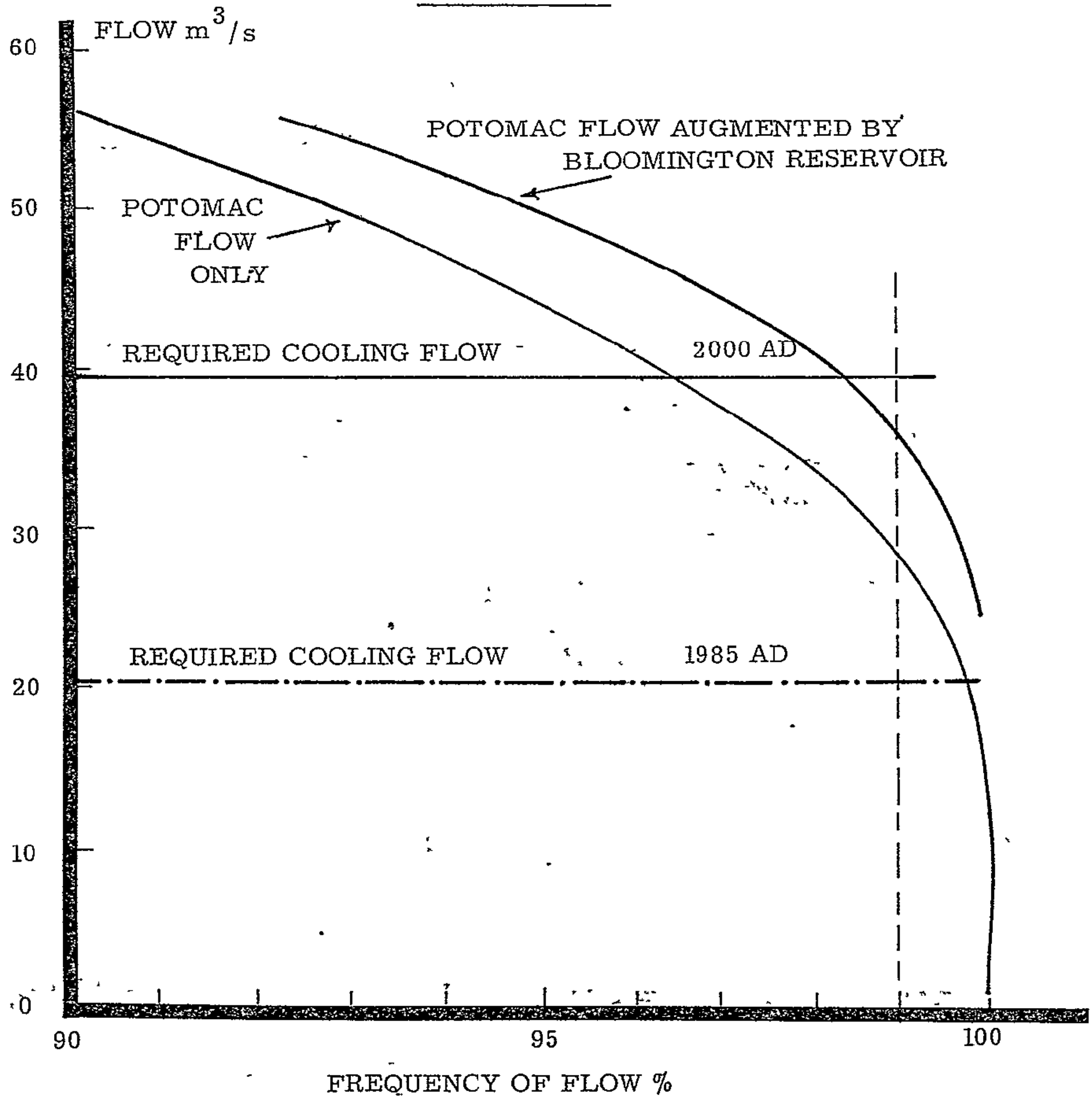
The 99% reliable flow specified by PEPCO would support an electrical energy generation of no more than 2.6 billion kilowatt-hours per year.

This (based on 4,500 hours yearly equivalent full-load operation) approximately equals 6 ten-thousandths of the expected U.S. electrical energy demand in 1985.

Since total U.S. river flow is equivalent to 375 Potomacs, all U.S. inland flow could support approximately 22% of the 1985 U.S. electrical energy demand, if each river were used once. In practice, some of the larger watercourses could support more than one plant, located serially along the river; on the other hand, much of the inland flow resides in small rivers, too small to support economically practical powerplants.

FLOW DURATION OF THE POTOMAC RIVER

Dickerson Site



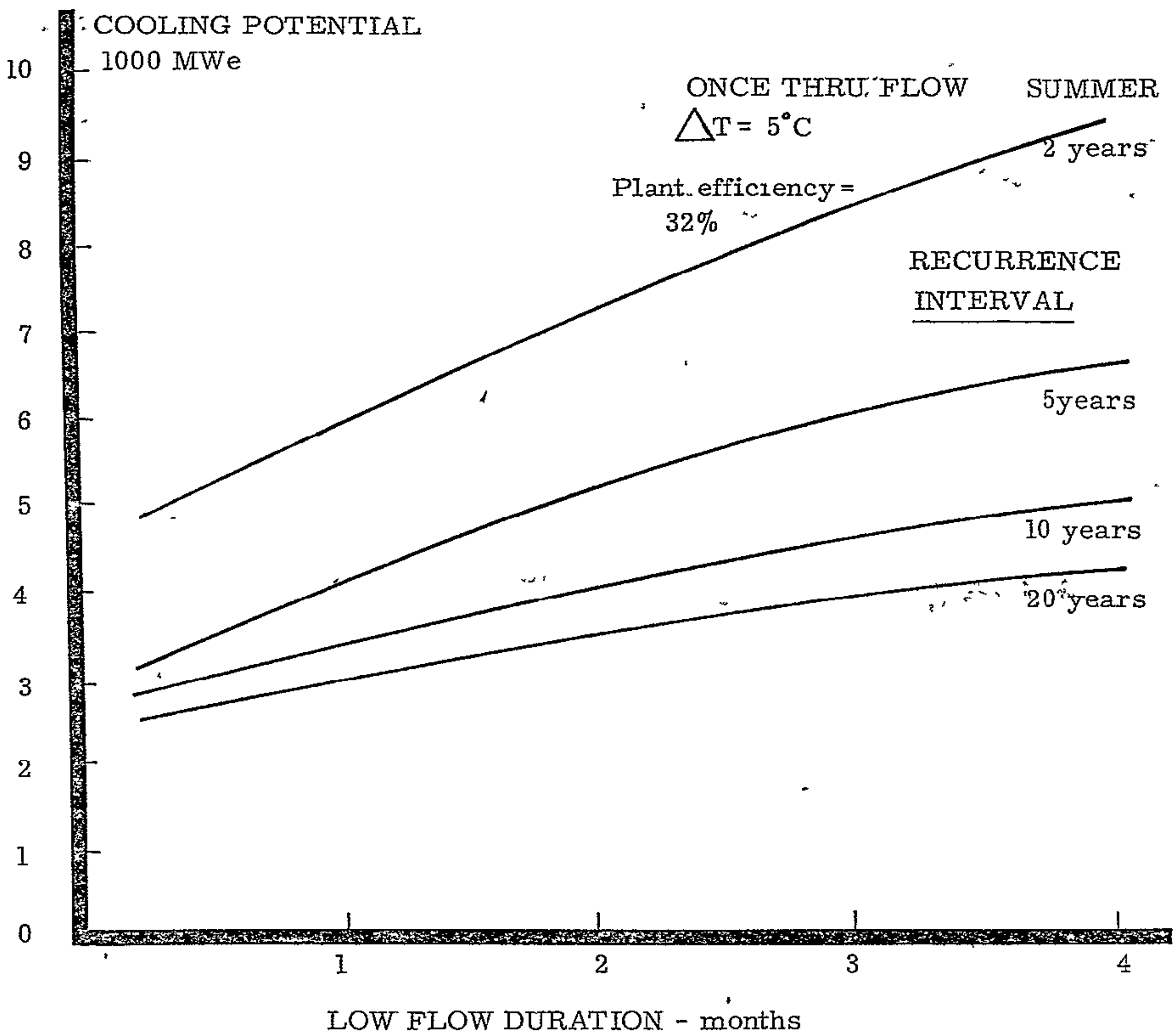
It can be seen from the preceding that cooling flow computations must be performed on a statistical basis, similarly to those for demand-supply matching.

When looked at in this way, the 99% reliable flow of the Potomac yields a low flow duration of 2.4 months for the 20-year recurrence interval (1% of 20 years = 2.4 months).

In turn, this yields a maximum cooling potential of 360 megawatts electric. For the typical 4,500 yearly hours of equivalent peak-load operation, this yields a total energy generation, when the cooling flow is used once, of 1.6 billion kilowatt-hours, or only 3.7 ten-thousandths of the U.S. electrical energy demand expected in 1985.

RELIABLE COOLING POTENTIAL OF THE POTOMAC

Potomac Mouth

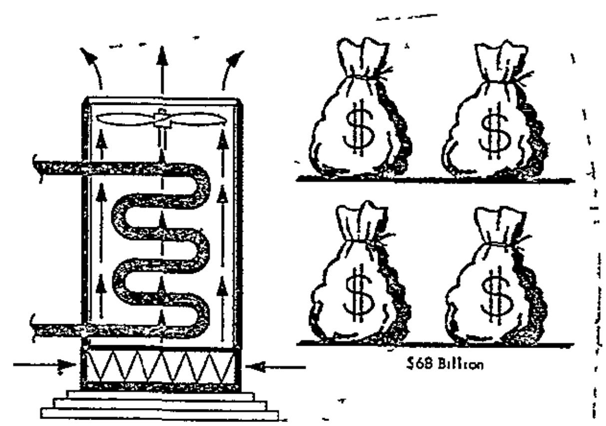


How to alleviate this problem? Current technology offers three basic cooling techniques.

The cleanest environmentally is the Closed Cycle technique, wherein waste heat is transferred to the atmosphere. It is also the most expensive.

COOLING TECHNOLOGIES

CLOSED CYCLE



U.S $5.4 Billion/Yr

COSTS REFERRED TO FORECASTED U.S.
POWER PLANT INVENTORY IN AD 2000.
IN 1970 DOLLARS.

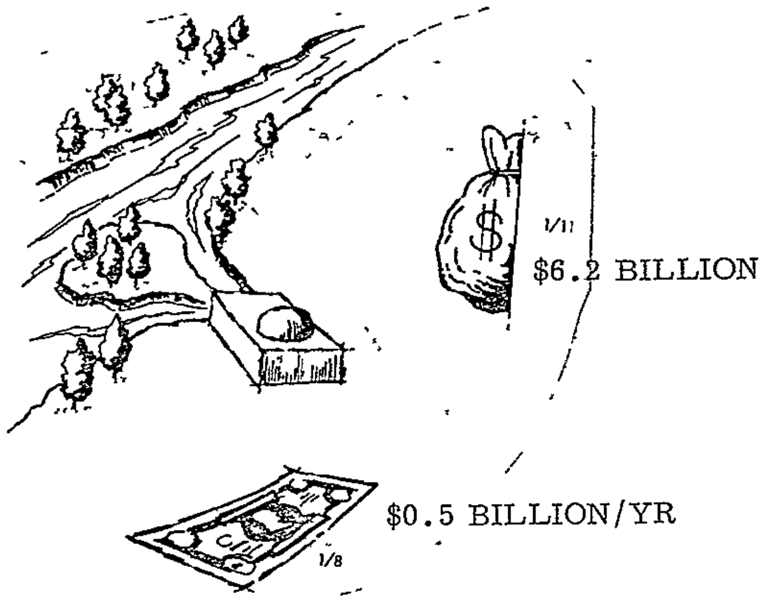
 = CAPITAL COSTS

 = ANNUAL MAINTENANCE AND SERVICE COSTS

The most economical technique, if sufficient flow is available, is the Flow Cooling Technique discussed previously.

COOLING TECHNOLOGIES

FLOW COOLING



COSTS REFERRED TO FORECASTED U.S.
POWER PLANT INVENTORY IN AD 2000
IN 1970 DOLLARS.

 = CAPITAL COSTS

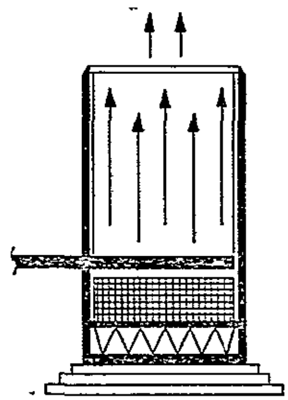
 = ANNUAL MAINTENANCE AND SERVICE COSTS

In between these two extremes lies the Evaporative Cooling Technique, which utilizes the water's heat of vaporization (600 Cal/Kg). Its problem is the large amount of steam generated and released to the atmosphere: approximately 100 m^3 (25,000 gallons) per minute of water equivalent per 1,000 megawatt electric output.

If all U.S. plants were to operate on this technique by 2000 AD, the equivalent of 29 Potomacs (116 million m^3/day) would be turned into steam continuously. This should not cause macroscale climate changes, but is sufficient to impact local microclimates.

COOLING TECHNOLOGIES

EVAPORATIVE COOLING



EXPRESSED

1/4
$17 BILLION

1/2
$2.7 BILLION/YR.

COSTS REFERRED TO FORECASTED U.S.
POWER PLANT INVENTORY IN AD 2000
IN 1970 DOLLARS.

 = CAPITAL COSTS

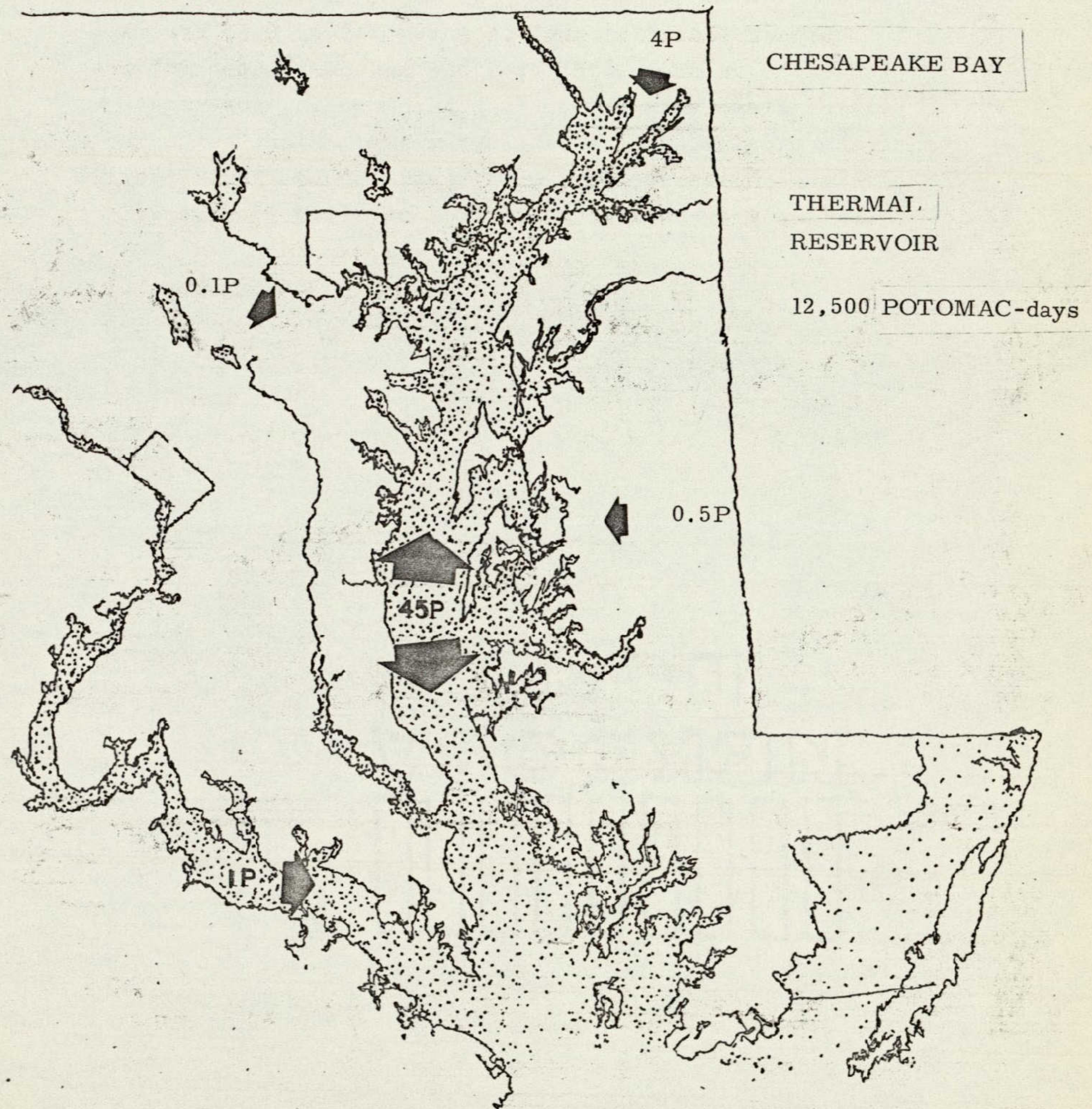
 = ANNUAL MAINTENANCE AND SERVICE COSTS

In net, current technology offers means to restrict the temperature of rivers to within the legally specified limits -- but at high cost.

The dilemma lies between preservation of riverine fish species and increased costs of electricity.

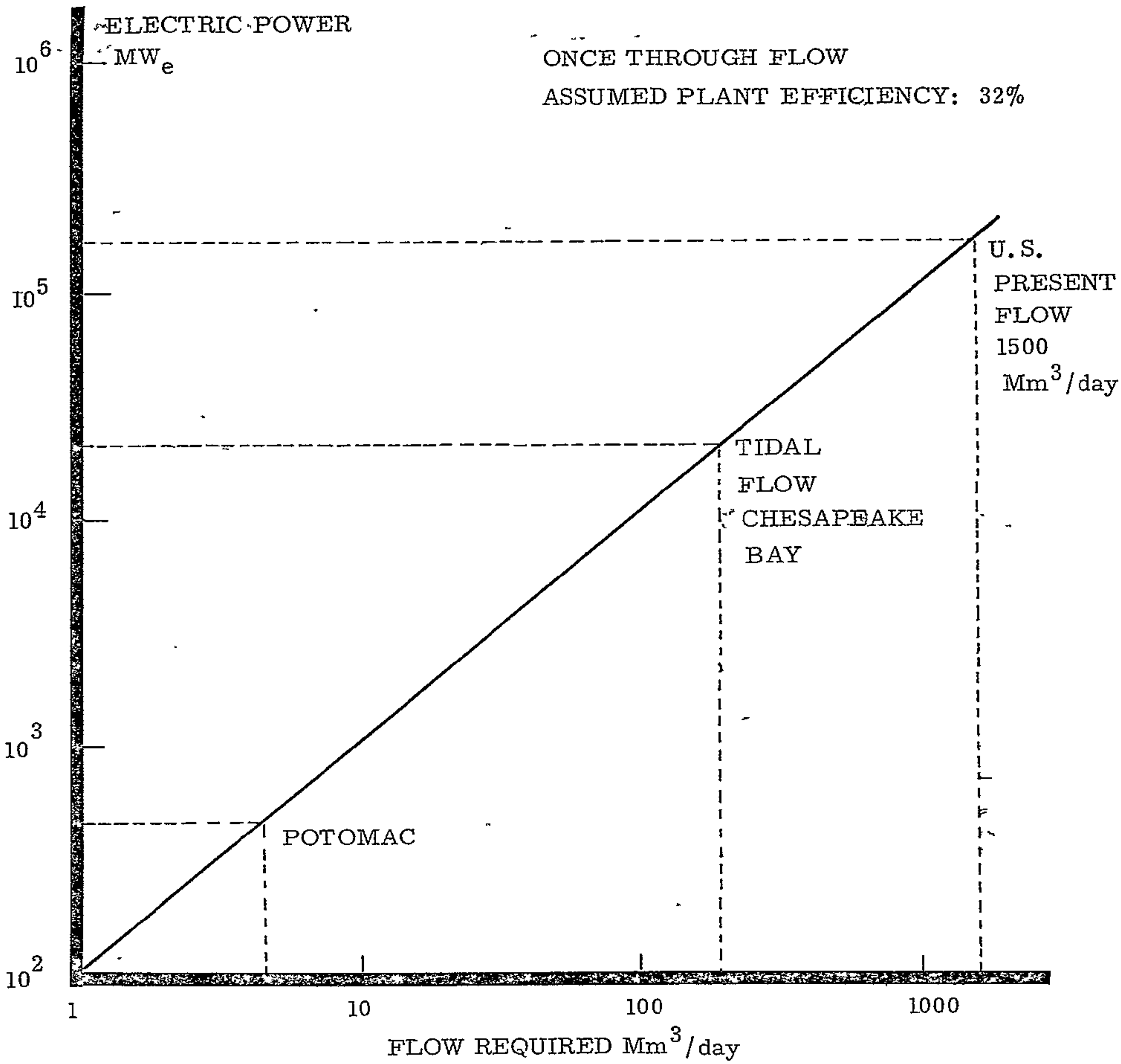
A possible alternative is offered by the potential tapping of estuarine tidal flows. Note for example that the Chesapeake Bay's daily tidal flow is one and one-half orders of magnitude greater than the flow of the Potomac. In addition, the volume within the Bay provides a thermal reservoir of very large capacity.

COOLING POTENTIAL OF TIDAL FLOW



Compare the total cooling potential of U.S. rivers - assumed to be used once through - and based upon 98% regulated flow, with the once-through cooling potential of the tidal flow of a single estuary. Eight estuaries like the Chesapeake Bay, completely tapped, could provide a cooling flow equivalent to that of all U.S. rivers.

RIVER FLOW REQUIRED FOR THERMAL COOLING OF POWER PLANTS

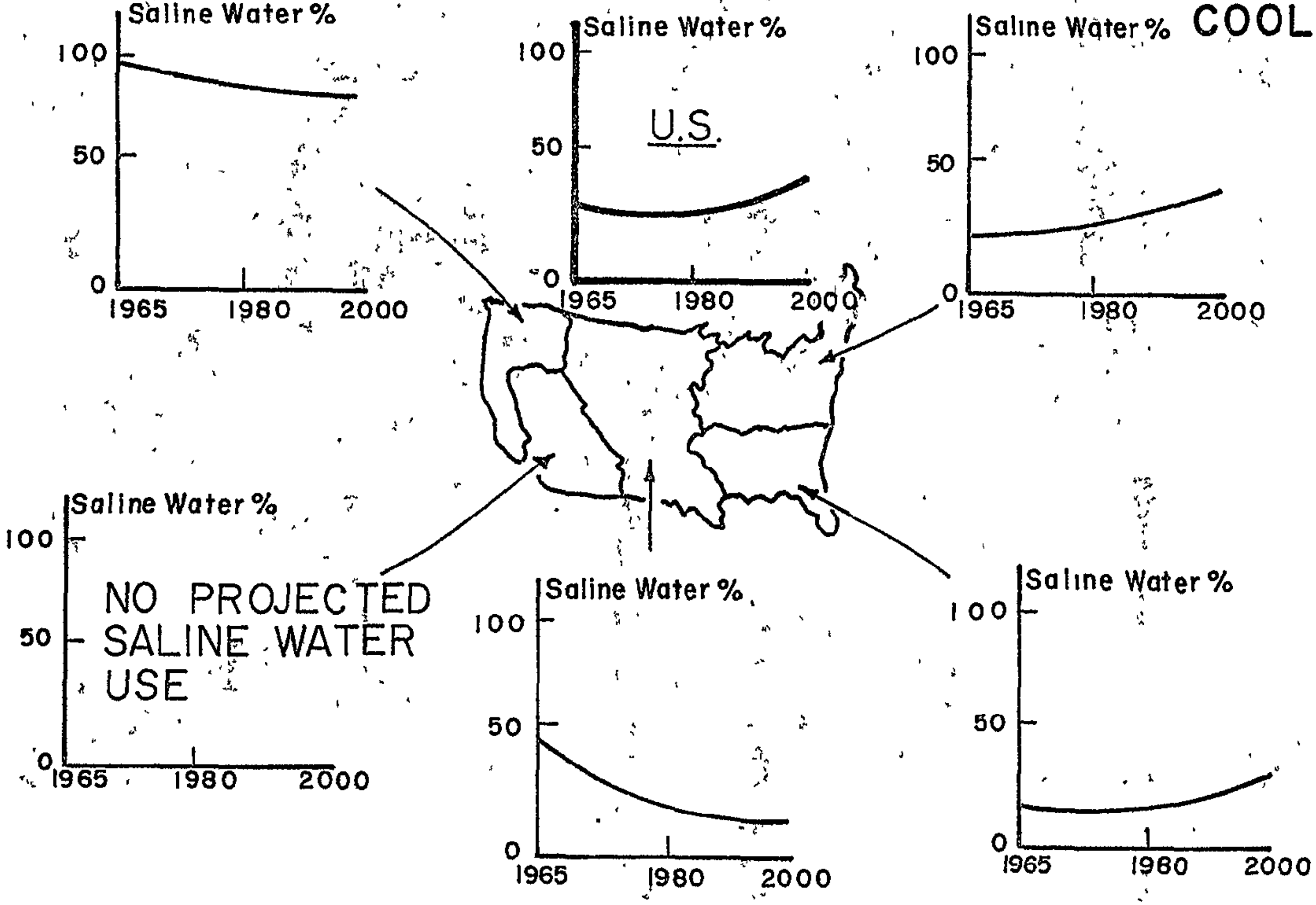


For these reasons, dependence upon estuarine and bay waters for electric energy generation cooling has already been exploited and is expected to grow in the future.

However, considerably more utilization of estuarine and tidal flow is needed to meet the forecasted U.S. electrical energy demands of the future.

Particularly important in this respect are the pressures exerted by conservationist groups who oppose and delay new plant construction.

THE INCREASING IMPORTANCE OF SALINE WATER FOR THERMAL COOLING

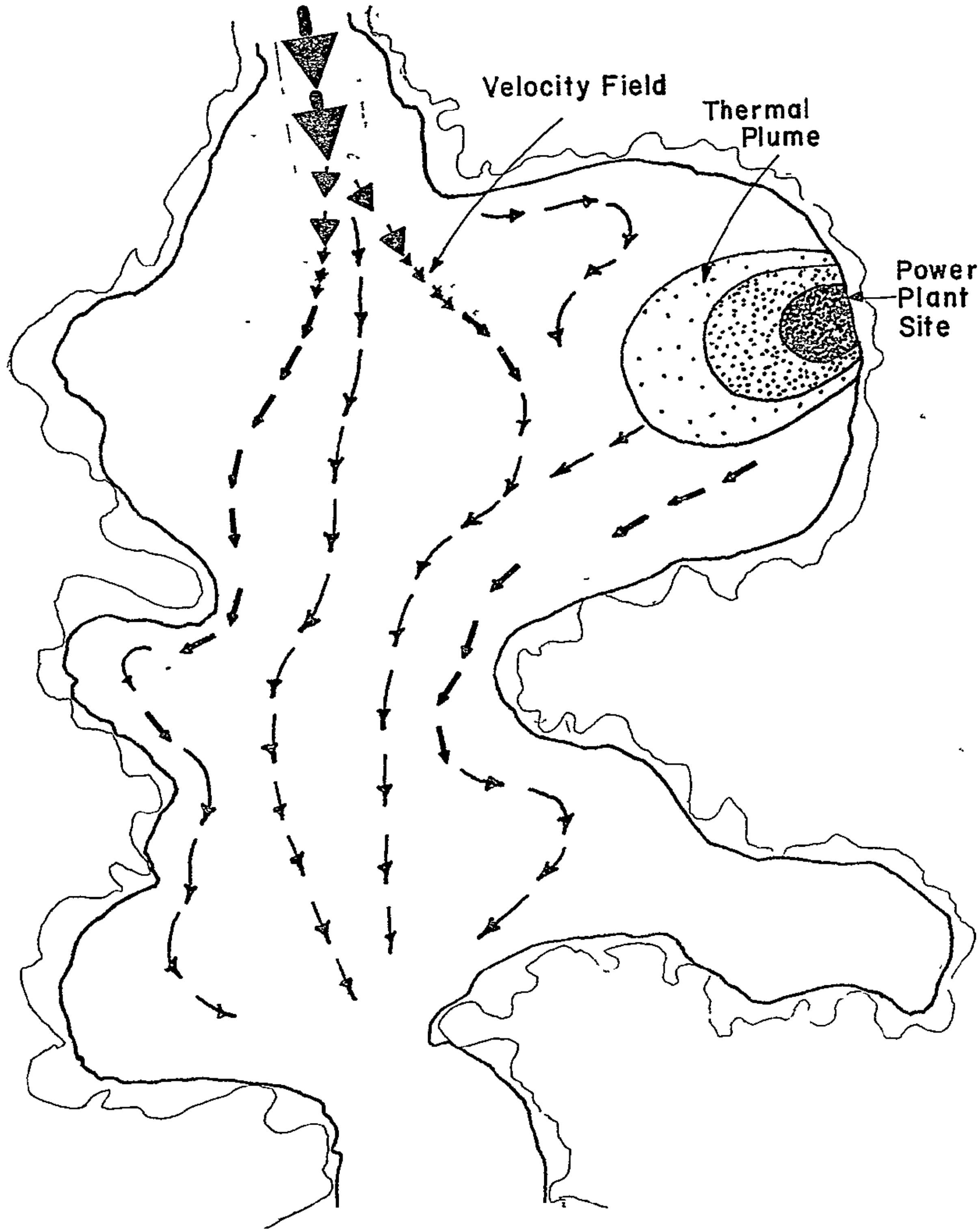


Optimal exploitation of estuarine and bay tidal flow requires detailed knowledge of the statistics of circulation and diffusion of the water mass in estuaries and bays.

Determination of these statistics is lengthy and costly by conventional surface methods: this is the principal reason why they are as yet insufficiently known.

This task is eminently amenable to application of remote sensing techniques.

TYPICAL ESTUARY CIRCULATION/DIFFUSION PATTERN



4. REMOTE SENSING PROGRAM STRUCTURE

Recapitulating, the economic significance of the principal Water Resource areas can be stated as follows:

(1) for the effects of water, in terms of yearly damages. This is the maximum benefit achievable from alleviation of the deleterious effects.

(2) for the demands for water, in terms of the prices paid yearly by water users. It should be understood that these prices undervalue the true worth of water, because of widespread policies of price support.

Onsite uses will be investigated in the next phase of the work. Nevertheless, indicative economic values are attached to these uses. These were based upon:

(1) for Inland Navigation: the yearly prices paid for waterborne freight.

(2) for Recreation: the yearly number of person-days spent upon inland waters for recreational purposes, multiplied by a "value" number computed by the Department of Interior.

(3) for Commercial Fishing: the landed price of yearly catch.

ECONOMIC SIGNIFICANCE OF WATER RESOURCES

Yearly U.S., 1975, Billion 1970 $

THE EFFECTS OF WATER

Excess Water		Waterborne Substances
Floods	2.5	NI
Avalanches	NI	
Wetlands	NI	**Hydrogeological Effects**
		NI

U.S. yearly total	
Effects :	2.5
Demands :	16.5-20.4

NI - Not investigated

( ) - Not investigated, estimated value

DEMANDS FOR WATER

Consumptive Users		Flow Users	
Agricultural	1.0	Hydropower	0.3
Industrial	4.4	Pollution Dilution	1.0-5.2
Domestic	0.4		
Municipal	0.4		

On-Site Users	
Inland Navigation	(0.5)
Recreation	(7.9)
Commercial Fishing	(0.3)

In spite of its economic significance and of the threat of approaching scarcity, no single U.S. Agency has overall responsibility for establishing water policy.

Closest to this role is the Water Resources Council, formed by Cabinet-level representatives from the principal Water Management Agencies. One of the Council's functions, effected through its Inter-Agency Committee on Water Resources, is to elaborate programs, policies, and activities for Congressional approval.

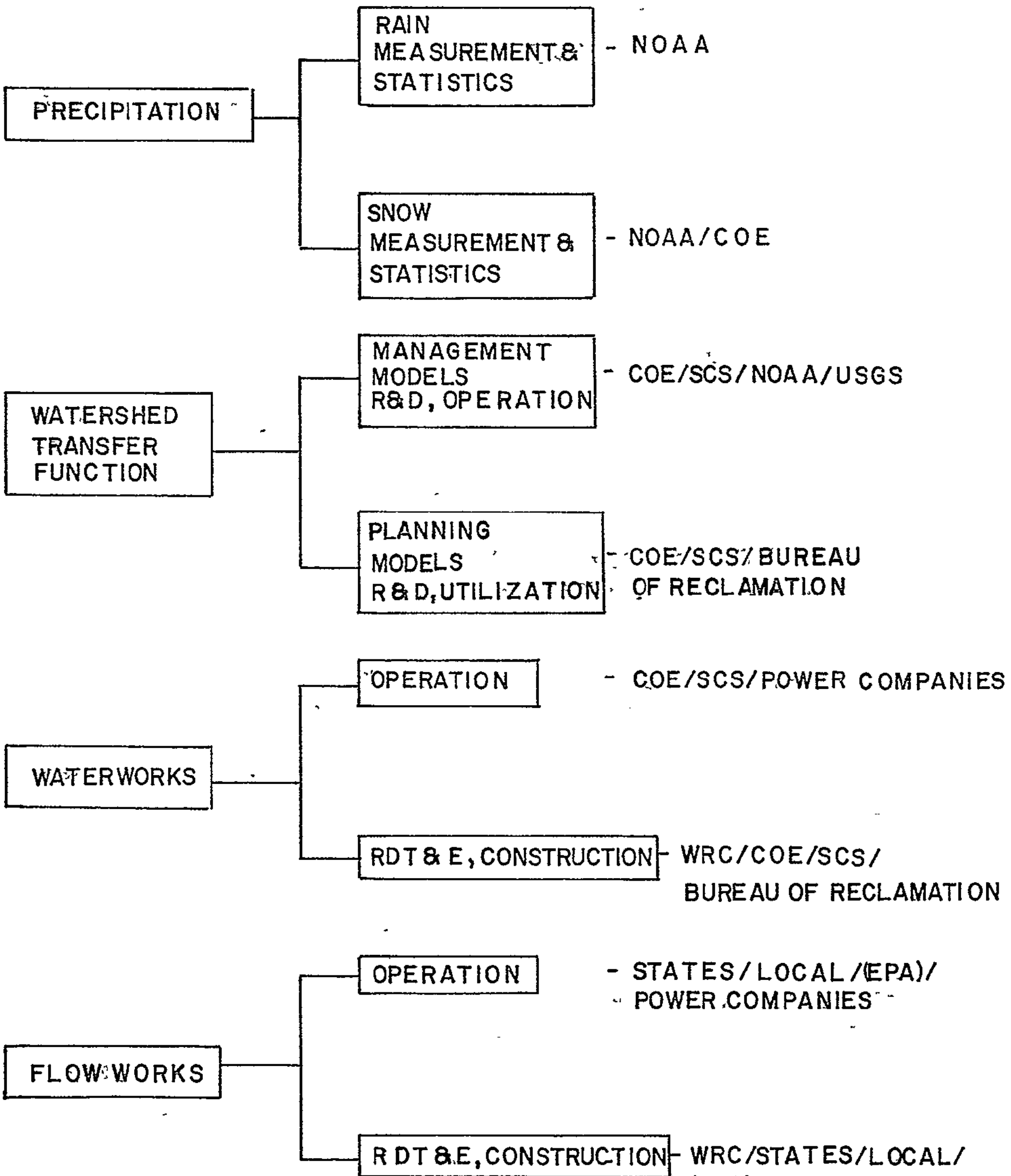
NOAA maintains the nationwide rain and snowgage network, provides real-time and statistical information on precipitation, and performs river flow forecasting.

USGS maintains the nationwide rivergage network, and provides real-time and statistical river flow information.

Corps of Engineers plans and implements major waterworks.

Soil Conservation Service performs a similar function for the smaller watersheds (less than 100,000 hectares).

States conduct waterworks planning and management for smaller projects. For large projects, they enlist the assistance of Federal Agencies, notably COE and SCS.



PRINCIPAL U.S. AGENCIES RESPONSIBLE FOR MANAGING WATER RESOURCES

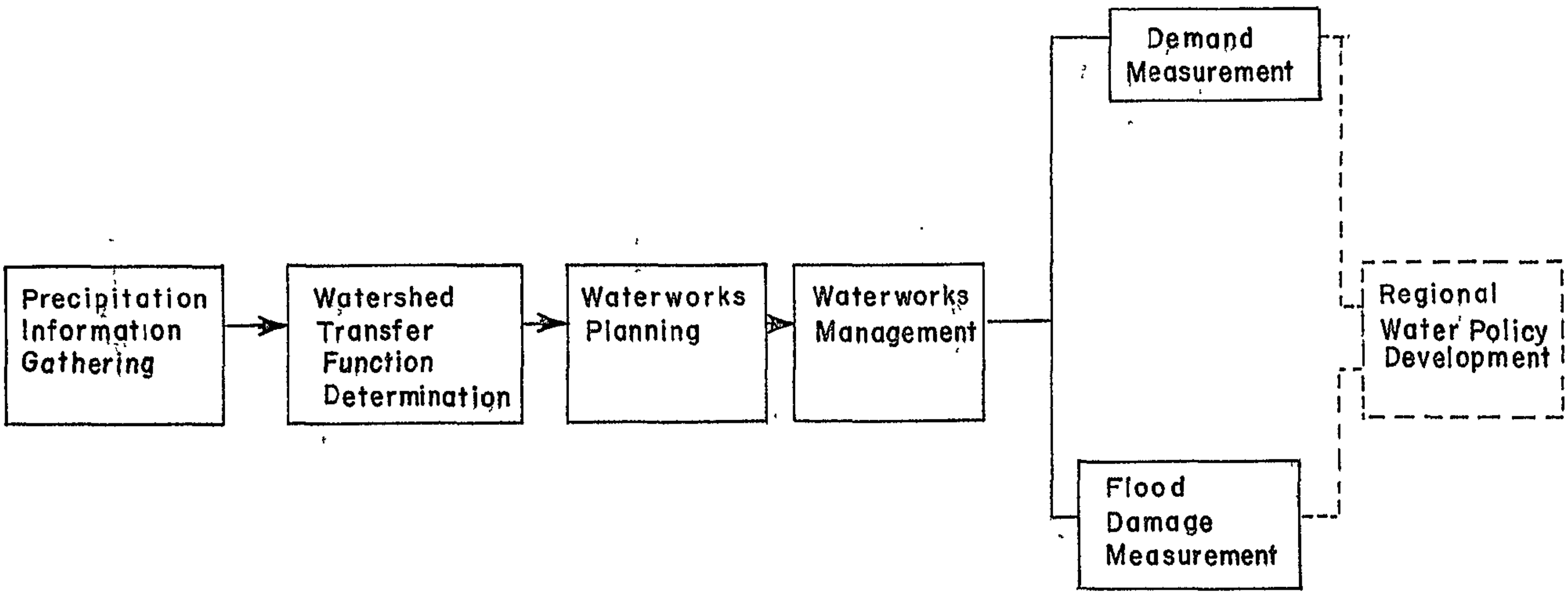
Although Water Resources activities are manifold, they can be boiled down to the major essentials shown opposite.

A significant conclusion emerges from the study performed so far: water demand requirements, added to the requirements for protection against the effects of water, will in the near future grow to be large, and in many cases, conflicting.

This fact, coupled with the high costs of increasing the reliable supply, points to the approaching need for setting up, at least in the water-scarce regions, specific Water Policies.

Such policies should guide, for example, decisions as to whether to implement Pollution Dilution versus Pollution Treatment procedures; as to whether to bound the regionally-produced electric energy, relying instead upon importation; as to how much additional water should be devoted to agriculture; and so forth.

Information gathering by Remote Sensing should prove of significant value in constructing the data base upon which to structure such Regional Water Policies.



THE MAJOR DRIVERS
IN WATER RESOURCES MANAGEMENT

The principal specific Water Resources areas, where remote sensing can significantly contribute to enhancing the efficiency of current methods, and/or to improve upon present practices, are recapitulated opposite.

The area of Waterworks Management remains to be analyzed in the next phase of this work.

The utilization of remote sensing for specific applications cannot generally be accomplished immediately, but requires precursor phases of information structuring and technique development and validation.

Precursor phases can be subdivided into four categories, shown opposite in descending order of content of precursor effort. Examples of each are:

- AD Development of Watershed Runoff Models, specifically tailored to accept and utilize remotely sensed information.

- TD Development of computerized techniques for distinguishing snowlines.

- TV Test and validation of rain and rivergage network via DCS

- X Mapping of areal extent of snow.

EVOLUTIONARY PHASES IN THE UTILIZATION OF REMOTE SENSING TO WATER RESOURCES APPLICATIONS

AD Applications Development - A program of data-gathering, correlation, ground truth measurements, required for, and precursor to, structuring a specific remote sensing application.

TD Technique Development - A program to determine specific aspects of remote sensing capability.

TV Technology Validation - A program to test and check out a specific set of hardware employed in remote sensing information gathering.

X Experiment - A quasi-operational program, wherein remotely sensed information is applied to improve cost/effectiveness of current procedures or to supersede current procedures with more advanced procedures.

PRINCIPAL NEAR-TERM REMOTE SENSING APPLICATIONS REQUIRING PRECURSOR DEVELOPMENT

(AD Type)

(1) WATERSHED MANAGEMENT MODEL
- Limited or no rivergage feedback
- Sensitive to watershed modification
- Capable of predicting subwatershed performance

(2) WATERSHED PLANNING MODEL
- Applicable to ungaged watersheds
- Sensitive to watershed alterations
- Capable of predicting subwatershed performance

(3) FLOOD DAMAGE MODEL
- Floodplain extent
- Floodplain economic model

(4) SNOWMELT RUNOFF MODEL

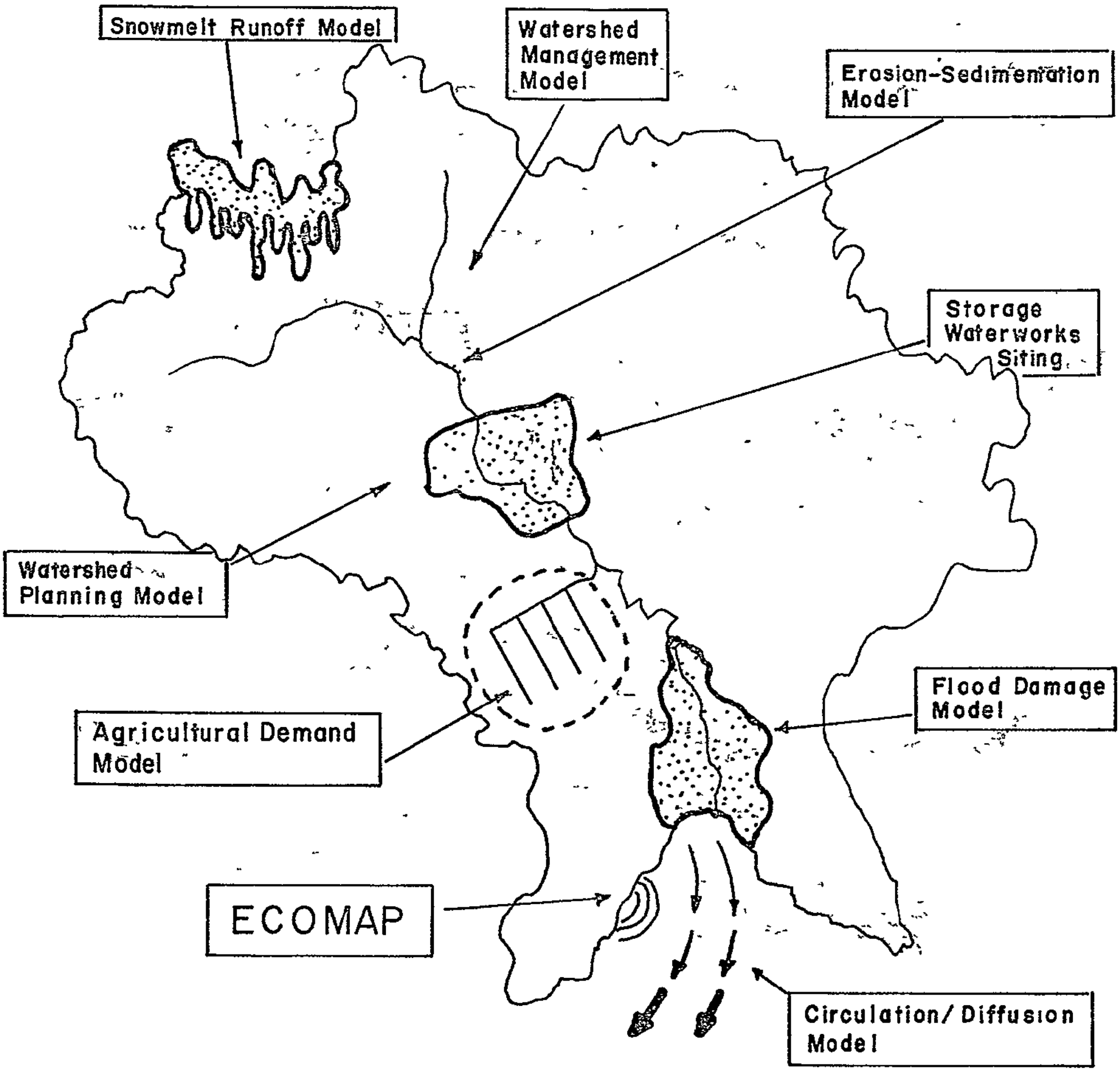
(5) STORAGE WATERWORKS SITING
- Physical Parameters
- Environmental/Social Impact Parameters

(6) AGRICULTURAL WATER DEMAND
- Real-time management of evapotranspiration demand

(7) CIRCULTATION-DIFFUSION MODEL
- Current pattern
- Dispersion pattern
- As a function of cyclic driving phenomena and of the statistical influence of the environment

(8) ECOMAP
- For Powerplant and Pollutant outlet siting
- Environmental/Social Impact Parameters

NEAR-TERM APPLICATIONS, AD TYPE



PRINCIPAL IMMEDIATE REMOTE SENSING APPLICATIONS (X Type)

(1) GEOGRAPHIC IMPORTANCE OF SNOW

Mapping areas where snowmelt is significant

(2) REAL-TIME PRECIPITATION MEASUREMENT

For strategically-located raingages of difficult access
For applications wherein quick response is significant (Flash-Flood Warning)

(3) TRANSIENT WATER SUPPLY

Playa lkes or equivalent, in areas where water supply is critical

(4) INUNDATION MAPPING

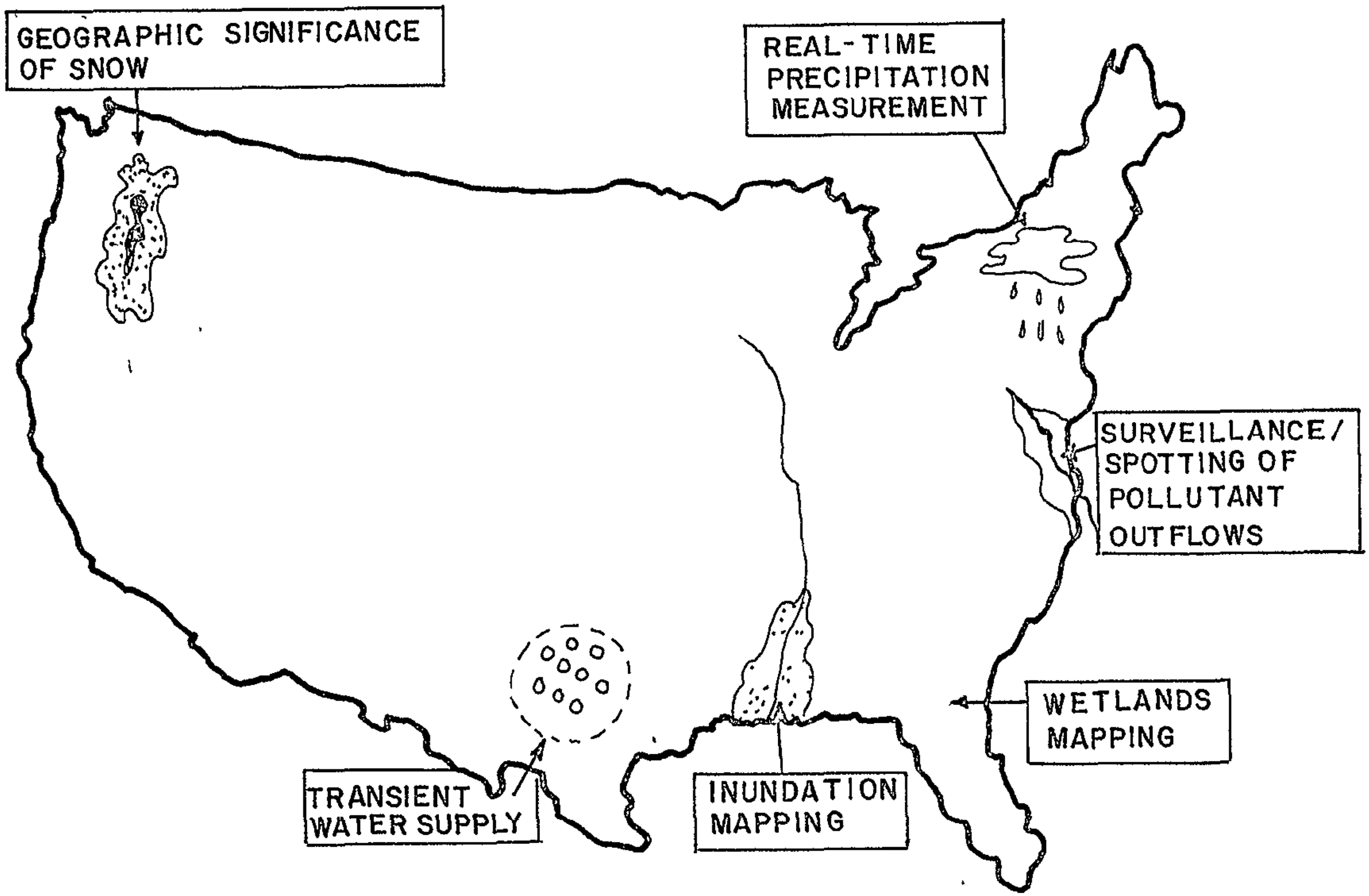
Measurement of flood extent as it occurs and comparison with predictions

(5) SURVEILLANCE/SPOTTING OF POLLUTANT OUTFLOWS

Qualitative detection of pollution plumes for subsequent ground action

(6) WETLANDS MAPPING

Not analyzed in this report



PRINCIPAL IMMEDIATE REMOTE SENSING APPLICATIONS
(X-TYPE)

5. REFERENCES

Approximately 5,000 Books, Reports, Publications and Technical Memoranda, U.S. and Foreign, were analyzed, abstracted and, where warranted by their content, synthesized in this report.

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5.2 PERSONAL COMMUNICATIONS

In the course of this work, and in accordance with the methodology set forth initially in this volume, a number of personal interfaces was held with Water Resources Users and Managers.

These resulted in:

(1) Valuable communications as to several important technical and administrative aspects of the field.

(2) Advice, suggestions and perspective as to the structuring of specific technical areas, and as to important problems faced by Water Resources Users and Managers.

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